frontiers in Materials

REVIEW
published: 25 March 2021
doi: 10.3389/fmats.2021.640102

A Review on Structural Configurations of Magnetorheological Fluid Based Devices Reported in 2018–2020

Dezheng Hua[1], *Xinhua Liu*[1,2]*, *Zengqiang Li*[2], *Pawel Fracz*[3], *Anna Hnydiuk-Stefan*[4] *and Zhixiong Li*[5]*

[1]School of Mechatronic Engineering, China University of Mining and Technology, Xuzhou, China, [2]Technology and Innovation Research Center of Jiang Yan EDZ, Taizhou, China, [3]Department of Manufacturing Engineering and Automation Products, Opole University of Technology, Opole, Poland, [4]Department of Power Engineering Management, Opole University of Technology, Opole, Poland, [5]Yonsei Frontier Lab, Yonsei University, Seoul, Republic of Korea

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***Correspondence:**
Xinhua Liu
liuxinhua@cumt.edu.cn
Zhixiong Li
zhixiong.li@yonsei.ac.kr

Specialty section:
This article was submitted to
Smart Materials,
a section of the journal
Frontiers in Materials

Received: 10 December 2020
Accepted: 19 January 2021
Published: 25 March 2021

Citation:
Hua D, Liu X, Li Z, Fracz P,
Hnydiuk-Stefan A and Li Z (2021) A
Review on Structural Configurations of
Magnetorheological Fluid Based
Devices Reported in 2018–2020.
Front. Mater. 8:640102.
doi: 10.3389/fmats.2021.640102

Magnetorheological fluid (MRF) is a kind of smart materials with rheological behavior change by means of external magnetic field application, which has been widely adopted in many complex systems of different technical fields. In this work, the state-of-the-art MRF based devices are reviewed according to structural configurations reported from 2018 to 2020. Based on the rheological characteristic, the MRF has a variety of operational modes, such as flow mode, shear mode, squeeze mode and pinch mode, and has unique advantages in some special practical applications. With reference to these operational modes, improved engineering mechanical devices with MRF are summarized, including brakes, clutches, dampers, and mounts proposed over these 3 years. Furthermore, some new medical devices using the MRF are also investigated, such as surgical assistive devices and artificial limbs. In particular, some outstanding advances on the structural innovations and application superiority of these devices are introduced in detail. Finally, an overview of the significant issues that occur in the MRF based devices is reported, and the developing trends for the devices using the MRF are discussed.

Keywords: magnetorheological fluid, magnetorheological fluid-based devices, structural configuration, magnetorheological fluid brakes, magnetorheological fluid clutch, magnetorheological fluid damper, magnetorheological medical devices

INTRODUCTION

Magnetorheological fluid (MRF), as a kind of smart materials, has been widely studied by scholars due to its controllable rheological properties in a few milliseconds (Jackson et al., 2018; Fu et al., 2020; Zheng et al., 2020). In the technical fields of vibration isolation (Rossi et al., 2018; Phu and Choi, 2019), energy absorption (Ahamed et al., 2016; Yoon J.-Y. et al., 2020), and actuation control (Hong et al., 2019; Zhang L. et al., 2019) et al., MRF has a unique advantage as the main part of the manipulation or regulation mechanism. Therefore, MRF based devices have great potential in structural optimization and innovative development and show outstanding performance in engineering (Hu et al., 2019; Yuan et al., 2019; Zhou et al., 2020) and medical fields (El Wahed, 2020).

MRF based devices are mainly based on four operational modes of MRF, including flow mode, shear mode, squeeze mode and pinch mode, which show different performance in various practical application requirements (Elsaady et al., 2020a). Using the above four operational modes, widely studied engineering mechanical devices mainly involve brake, clutch, damper, and mount etc. (Ahamed et al., 2018). Because the MRF can generate a reliable and stable magnetorheological

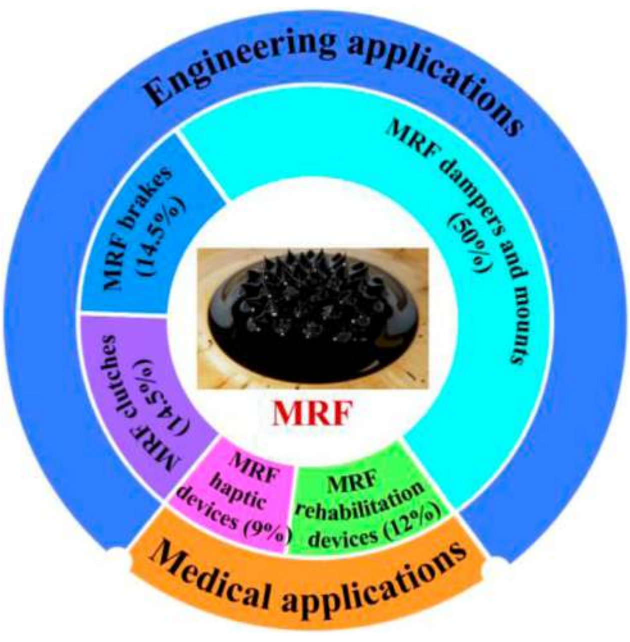

FIGURE 1 | Classification of MRF based devices with proportions according to the referred literatures.

phenomenon with fast response and strong controllability in the magnetic field environment (Juan et al., 2011), MRF based devices generally have a low failure rate and high regulating ability. However, with the change of the production environment and the improvement of application requirements, these MRF based devices have gradually exposed some defects, such as weak magnetic field (Lee et al., 2018), unstable MRF because of overheated electromagnetic coils (Wang et al., 2019b), settlement of MRF in the idle state (Bastola et al., 2019), leakage of MRF (Tu et al., 2019), and an overall large and bulky devices volume (Li J. H. et al., 2018). Therefore, in view of the various problems in practical applications, many scholars have proposed different improvements and optimization methods based on traditional structures, which has greatly enhanced the performance of the MRF based devices.

Furthermore, different from the above application types, the MRF has been further developed, and has in recent years become an important part of the haptic feedback system (Song et al., 2018b) and artificial limbs (Pandit et al., 2018) in the medical field. In the haptic feedback system based on the MRF, using the controlled rheological characteristics, a resistance environment similar to the real sense of touch is generated and transmitted to the operator, which is widely applied to the teleoperated catheter operating system (Song et al., 2018a) or intelligent haptic interface devices (Topcu et al., 2018). Moreover, in some medical auxiliary and customized devices, such as prostheses (Jing et al., 2018; Zhou and Liu, 2020), rehabilitation protection devices (Zhou et al., 2020), and skeletons (Veronneau et al., 2018), the MRF has been widely studied for advantages of adjustable stiffness and easy structure integration. Based on these specific applications, novel product structures and design methods are proposed using the MRF, which fully reflects the irreplaceable role of the smart material in many advanced technologies.

Having thus described some basic concepts and providing a broad categorization, some typical MRF based devices are investigated in engineering and medical applications from 2018 to 2020. In this work, 104 academic articles from these 3 years are used as a reference, reporting on the novel structure configurations, design purposes, and advantages of MRF based devices. Based on the above classification introduction, the proportions of different development directions are shown in **Figure 1**. Furthermore, some drawbacks of the MRF filled devices are also summarized. After a discussion, conclusions, and outline, prospects for the development of MRF based devices are presented.

MAGNETORHEOLOGICAL FLUID BRAKES IN ENGINEERING APPLICATIONS

A brake is a device with the function of making moving parts (or moving machinery) slow down, stop or maintain the stopped state, which is widely used in lifting transportation equipment, mining equipment, construction engineering equipment, and marine ship equipment. Increasing brake torque, eliminating hysteresis time, optimizing device volume and weight, and reducing energy consumption are the main directions of developing new MRF brakes (Bazargan-Lari, 2019; Zhu et al., 2019). Some MRF brakes reported from 2018 to 2020 are summarized in **Table 1**.

In 2018, a radial multi-pole-and-layer MRF brake with higher torque and torque density was proposed, shown in **Figure 2A** (Wu et al., 2018). In this design, two superposition magnetic fields are generated by inner and outer coils with 12 magnetic poles, and four media layers of MRF are located in these coils. The braking characteristics of the device are significantly improved, but the added coils increase the overall weight and energy consumption. Furthermore, an MRF brake was designed with a multi-drum architecture, shown in **Figure 2B** (Qin et al., 2018). The device is compact and light-weight, generating four gaps of MRF, which increases the shear area but also requires higher manufacturing accuracy. In order to enhance the braking torque, except the above structural changes, a configuration of an MRF brake with three coils on each side of the brake housing was designed, shown in **Figure 2C** (Nguyen et al., 2019). The device provides better braking performance than a traditional single side-coil MRF brake. However, the device is also unable to avoid the defects of being heavy, having high energy consumption, and temperature interference. Different from the above design solution, an MRF brake was proposed to avoid meaningless loss, where permanent magnets were used to attract MRF into a neighboring gap, shown in **Figure 3A** (Shamieh and Sedaghati, 2018). Through eliminating contact of the MRF and rotor, power loss due to the zero-field viscous torque is decreased. On the other hand, in the braking state of the device, the effective shear area of MRF is small and the braking torque is limited. Moreover, an elastomeric baffle device with MRF was proposed and applied for the electronic joystick machine shown in **Figure 3B** (Elliott and

TABLE 1 | Novel MRF brakes in 2018–2020.

No.	References	Type	Improved method
1	Zhu and Geng (2018)	Brake with shear and differential pressure mode	Simulating Wankel engine configuration to realize intelligent brake quickly
2	Wu et al. (2018)	Multi-pole-and-layer type brake with shear mode	Using two layers structure with six pairs of coils to improve magnetic field strength
3	Qin et al. (2018)	Multi-drum type brake with shear mode	Adding the number of layers in the drum to increase the working area of MRF.
4	Nguyen et al. (2019)	Multi-coil type brake with shear mode	Adopting three coils on each side of the brake housing to improve magnetic field strength
5	Shamieh and Sedaghati (2018)	Permanent magnets and coil type brake with shear mode	Using permanent magnets to absorb MRF to reduce the energy loss caused by zero field viscosity
6	Elliott and Buckner (2018)	Piston type brake with shear mode	Combining MRF and baffle with simple structure to control the electronic joystick
7	Zhu et al. (2019)	Disc-and-drum type brake with shear mode	Optimizing structure size and verifying phenomenon of shear thinning in high speed
8	Dai et al. (2019)	Rotary micro brake with shear mode	Combining with turbine generator with compact structure
9	Qin et al. (2019)	Multi drum type brake with shear mode	Designing a hollowed casing structure to fill with actuator
10	Wang et al. (2019a)	Disc type brake with squeeze and shear mode	Using squeeze-shear mode and water-cooling way simultaneously to improve the brake performance
11	Wang and Bi (2020)	Disc type brake with squeeze and shear mode	Adopting an automatic squeeze and shear mode to improve the torque output
12	Zhang D. et al. (2020)	Disc type brake with shear mode	Coupling multiple brakes to conduct the torsional forward of snake-like robot

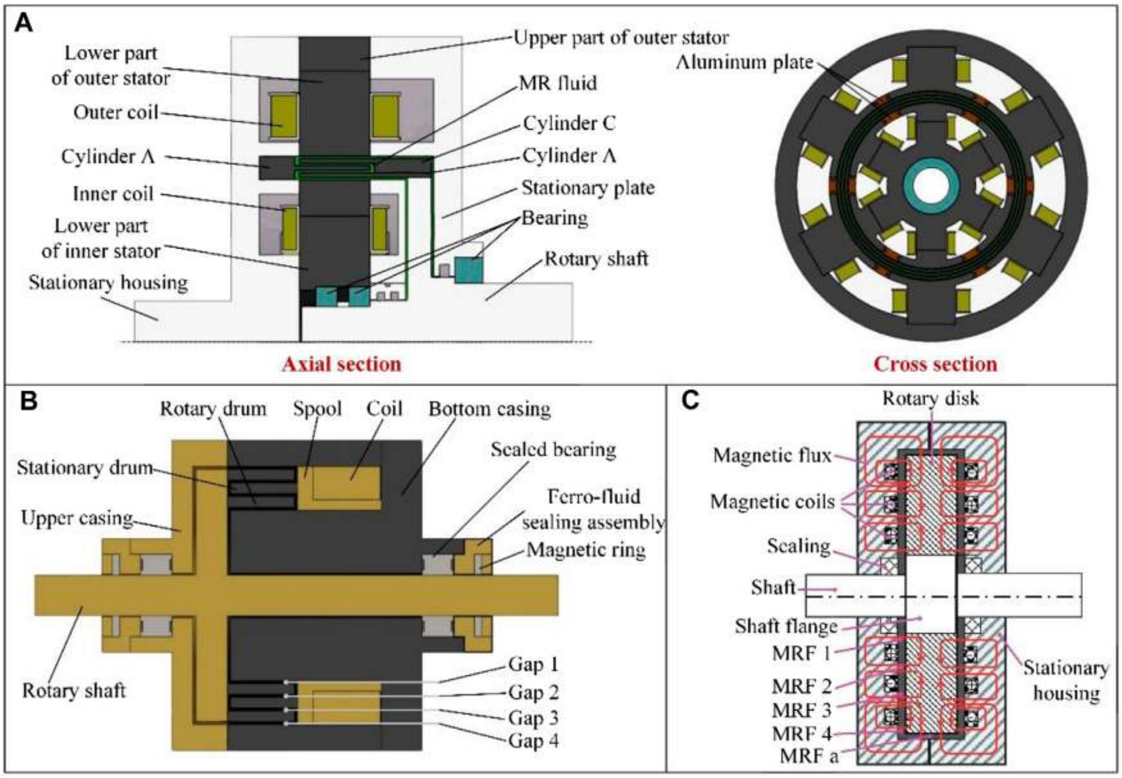

FIGURE 2 | (A) Multi-pole-and-layer MRF brake (Wu et al., 2018). **(B)** Multi-drum MRF brake (Qin et al., 2018). **(C)** Multiple side-coil MRF brake (Nguyen et al., 2019).

Buckner, 2018). The device provides controllable resistance to axial motion of the center shaft and has the advantages of reducing cost and complexity.

In 2019, a micro-brake was proposed to regulate a miniature turbine generator based on MR fluid and MR grease, respectively, shown in **Figure 4A** (Huang et al., 2018; Dai et al., 2019). In the simple device, an electromagnetic coil fills internal space, and low permeability materials are used to maximize the magnetic field density. The brake can improve enough resistance when the turbine generator is working at high wind speeds. Similar to a compact structure, a novel hollowed multi-drum MRF brake was proposed to deal with the magnetic hysteresis, shown in **Figure 4B** (Qin et al., 2019). The device has a multi-drum mode, and a hollowed casing filled with actuator provides the

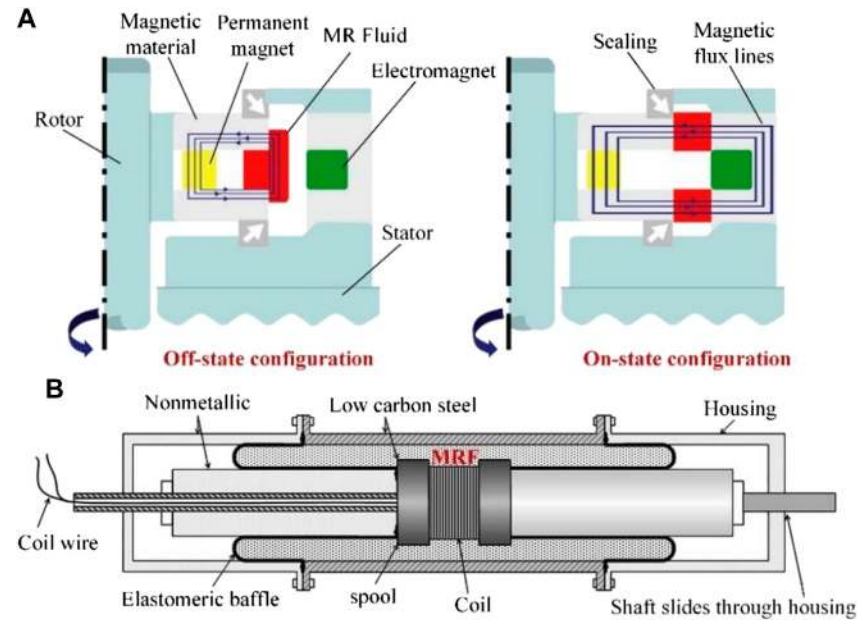

FIGURE 3 | (A) MRF brake without zero-field viscous torque (Shamieh and Sedaghati, 2018). **(B)** Elastomeric baffle MRF device (Elliott and Buckner, 2018).

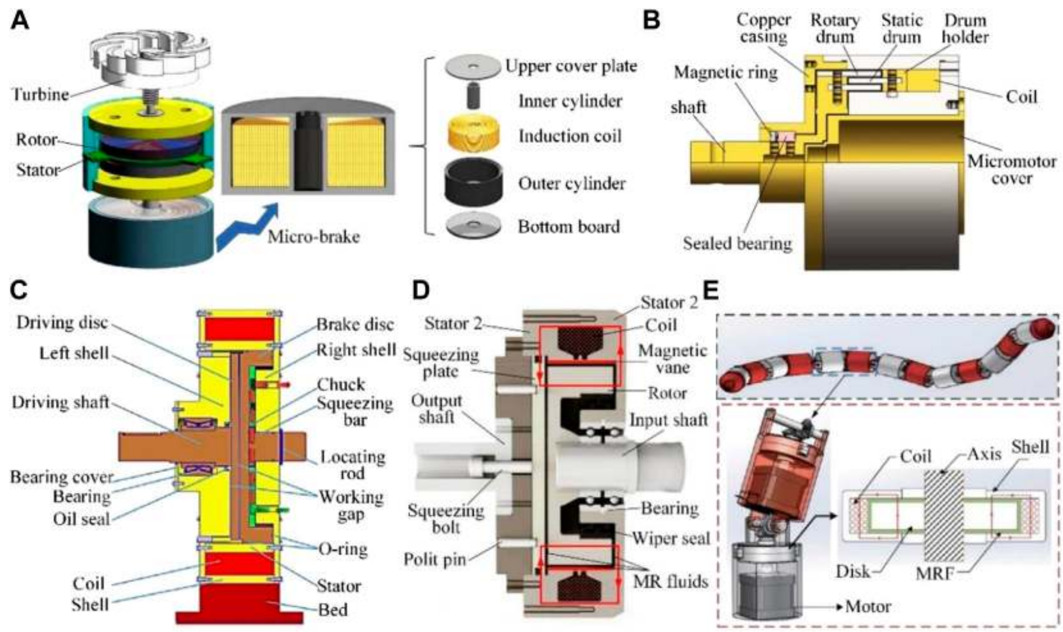

FIGURE 4 | (A) Rotary micro-brake (Dai et al., 2019). **(B)** Multi-drum MRF brake (Qin et al., 2019). **(C)** High-torque squeezing MRF brake (Wang et al., 2019a). **(D)** MRF brake with squeeze-shear mode (Wang and Bi, 2020). **(E)** Snake like robot with MRF actuators (Zhang D. et al., 2020).

important reference of the composite structure. But these compact structures tend to increase the MRF temperature and cause the braking torque to decrease. Then, a squeezing brake was presented to reduce the effect of temperature on MRF, shown in **Figure 4C** (Wang et al., 2019a). In this device, several flumes are designed to dissipate the heat of MRF and brake disc, the water-cooling method effectively improves the working time and maintains high brake torque. However, the flumes increase the size of the brake and require the addition of water circulation equipment. Furthermore, in 2020, an MRF brake under squeeze-shear mode was designed, in which a squeezing bolt was presented to produce compressive force for transmission

TABLE 2 | Novel MRF clutches in 2018–2020.

No.	References	Type	Improved method
1	Fernandez et al. (2018)	Drum type clutch with shear mode	Using a steel cylinder moved in and out the clutch device to adjust magnetic field of permanent magnet.
2	Wang W. D. et al. (2019)	Disc type clutch with shear mode	Providing a human-robot interaction MRF clutch and optimizing structure sizes
3	Wu et al. (2019)	Multi hollow disc type clutch with shear mode	Designing a complex transmission disc with a plurality of magnetic conductive columns and flumes for cooling liquid
4	Kikuchi et al. (2020)	Multi disc type clutch with shear mode	Presenting a multi-clutch coupling scheme
5	Olszak et al. (2019)	Valve type clutch with flow mode	Simulating the structure of electric pump and replacing oil fluid with MRF to realize the power transmission control
6	Yang and Chen (2019)	Drum type clutch with shear mode	Proposing a wedge-shaped clearance between the inner and outer cylinders for uniform distribution of magnetic field
7	Wang X. et al. (2019)	Conical type clutch with shear and squeeze mode	Adopting shape memory alloy to provide squeeze mode and improving torque output performance
8	Xiong et al. (2019)	Disc type clutch with shear and squeeze mode	Adopting electrothermal shape memory alloy to provide squeeze mode and improving transmission performance
9	Binyet and Chang (2020)	Disc type clutch with shear mode	Changing the position of permanent magnets to control the working mode of MRF and reducing energy consumption
10	Pilon et al. (2020)	Disc type clutch with shear mode	Designing a 3D screw flight made of MRF and improving the durability of device

performance, and a magnetic vane was set to ensure that a magnetic flux crosses both sides of the rotor, shown in **Figure 4D** (Wang and Bi, 2020). Utilizing the combined mode, the MRF device generated higher torque compared to those without compression. Moreover, an MRF brake with adaptive stiffness control was applied to a snake-like robot shown in **Figure 4E** (Zhang D. et al., 2020). Although this device has only the most basic brake structure, a number of MRF brakes are assembled head to tail, that is, the brake can also be regarded as an actuator. By flexibly controlling the output torque of each joint MRF brake, the twisting motion of the snake-like robot can be realized. Since the motion of each joint is different, the actuators with MRF need to be controlled, separately.

MAGNETORHEOLOGICAL FLUID CLUTCHES IN ENGINEERING APPLICATIONS

A clutch is a commonly used mechanism in transmission or actuation equipment and can separate or engage motion components at any time (Tian et al., 2018; Wang W. D. et al., 2019). As a special power switch, a high-quality clutch has some basic requirements such as a smooth joint, rapid and complete separation, a small sized exterior profile, good wear resistance, adequate heat dissipation capacity, is easy to operate, and is labor saving. Aiming to realize the above working performance, new clutches based on MRF have been extensively studied and have unique advantages in many engineering applications. Some MRF clutches from 2018 to 2020 are summarized in **Table 2**.

In 2018, an MRF clutch was presented using permanent magnets, which is covered by a steel cylinder (Fernandez et al., 2018). The steel cylinder is adjusted to move the clutch device in and out and alters the intensity of the magnetic field around MRF to vary transmitted torque. This method can quickly control the magnetic field without changing the position of permanent magnets. In 2019, an MRF transmission device was proposed for high-power applications, shown in **Figure 5A** (Wu et al., 2019). It can be seen from the schematic configuration that a multi-hollow transmission disc was designed, and each single disc has a plurality of magnetic conductive columns and flumes for cooling liquid. The structure design with maximum output torque of 1880 N m and slip power of 70 kW has great working performance. Because of the large working area of the cooling liquid and MRF, the sealing requirements and production costs for this device are high. Based on the coupled operation mode, a multi-disc MRF clutch was presented, two of which are fixed on the casing and shaft, shown in **Figure 5B** (Kikuchi et al., 2020). Utilizing the clutch, a new actuator with flexible torque control can be assembled for the haptic device. Moreover, a hydrodynamic MRF clutch shown in **Figure 5C** was proposed, where the centrifugal forces in the pump actuate MRF to flow through the channel placed in the magnetic valve and the cross over turbine (Olszak et al., 2019). Thus, the turbine torque is controlled by regulating excited voltage of the electromagnetic coil. On the other hand, there are higher restrictions on particle size and precipitation characteristics of MRF in this device. In addition, to address the problem of an uneven magnetic field, a wedge clearance was designed in a drum type MRF transmission device (Yang and Chen, 2019). The outer cylinder is connected with the driving shaft, and the inner cylinder with an inclined surface is connected with the driven shaft. MRF fills the wedge-shaped clearance between the inner and outer cylinders. The results show that when the wedge angle is about 1.074°, the magnetic induction intensity in the working gap has the most uniform distribution, which is conducive to a stable and accurate torque output.

In order to maintain a stable working performance and to improve transmission torque, a hybrid model combined with MRF and shape memory alloy was proposed by Wang X. et al. (2019) and Xiong et al. (2019) shown in **Figure 6A**. When the temperature reaches a critical phase transition value, the electrothermal shape memory spring outputs pressure and pushes the friction disc to squeeze the active disc. The MRF

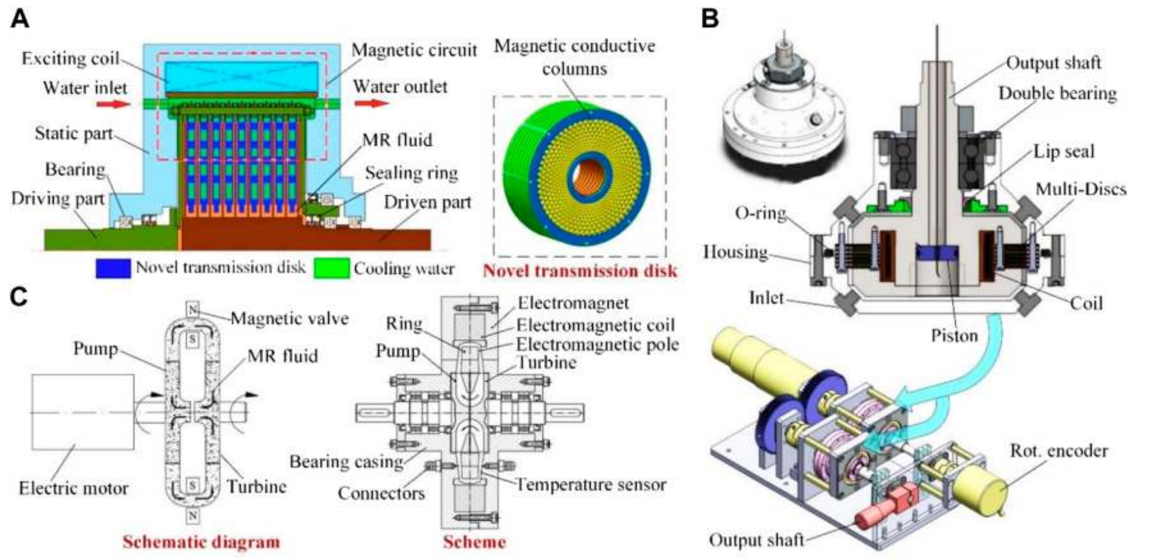

FIGURE 5 | (A) High-power MRF clutch (Wu et al., 2019). **(B)** Multi-layered disc MRF clutch and twin-driven MRF actuator (Kikuchi et al., 2020). **(C)** Hydrodynamic clutch with MRF (Olszak et al., 2019).

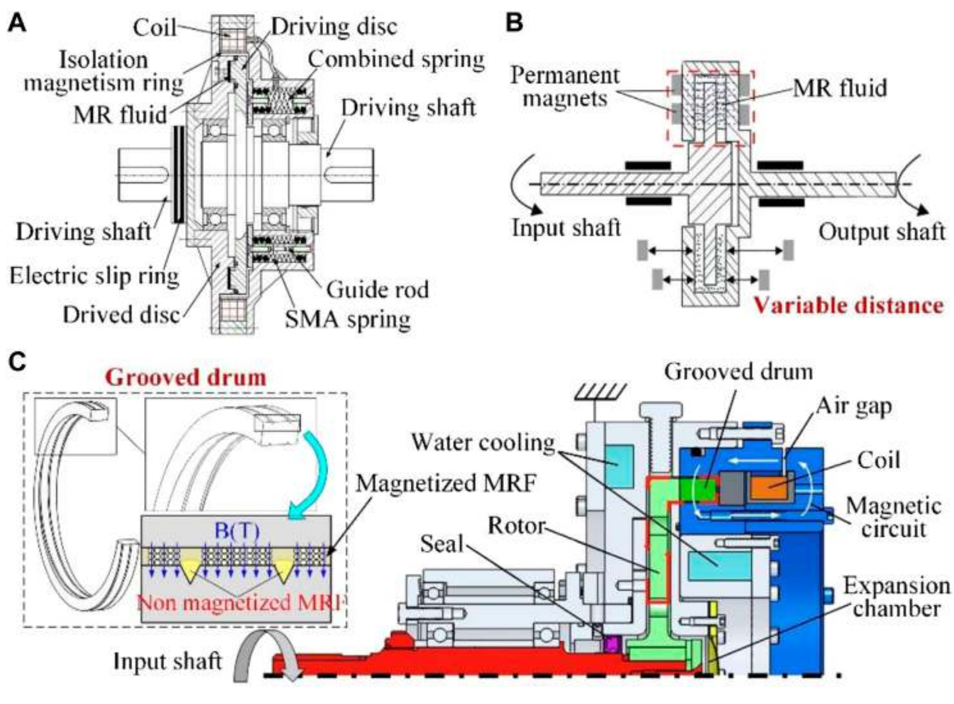

FIGURE 6 | (A) MRF and shape memory alloy combined clutch (Xiong et al., 2019). **(B)** MRF clutch-brake with permanent magnets (Binyet and Chang, 2020). **(C)** MRF clutch with grooved drum (Pilon et al., 2020).

device adds the squeezing working mode with a compact structure, but the operating time of this mode is limited by temperature. In 2020, with the aim to reduce chattering, an MRF clutch-brake was proposed, as shown in **Figure 6B** (Binyet and Chang, 2020). In this device, permanent magnets are placed in a casing that can axially slide, which allows a good shielding from the magnetic flux in the off mode. Permanent magnets are conducted to mechanically excite the device, offering simplicity and a reliable operation. However, the magnetic field gradient on the surface of permanent magnets is large and the

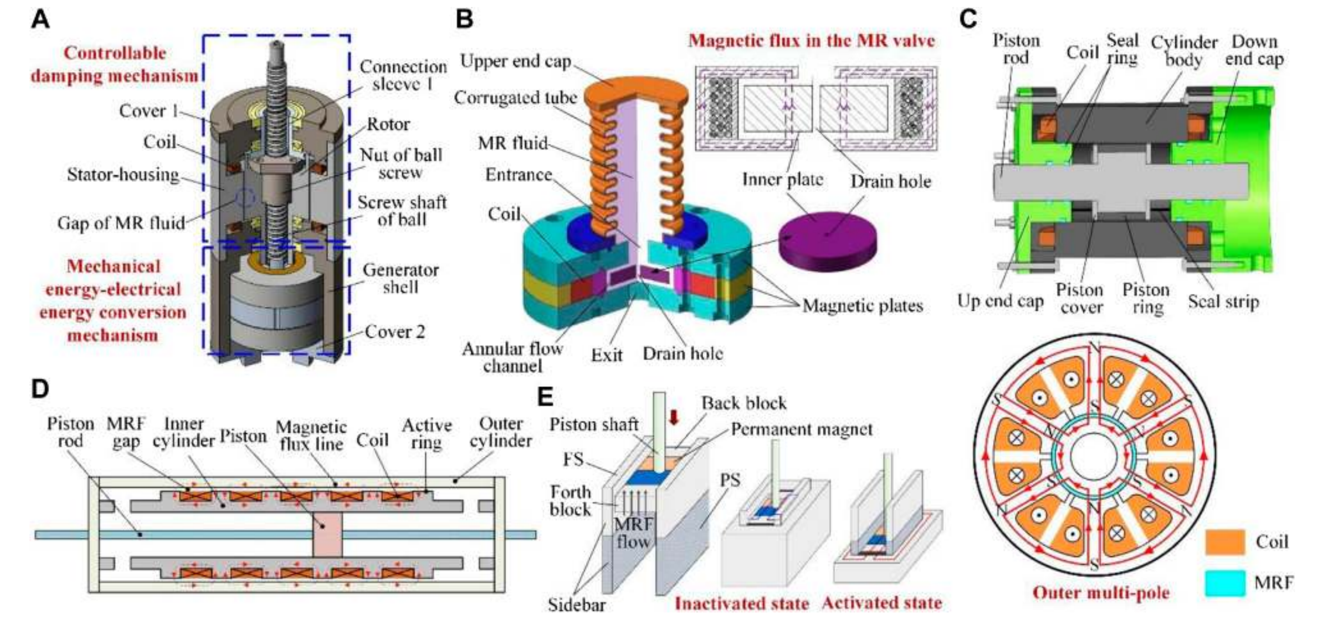

FIGURE 7 | (A) Power-generated MRF absorber (Bai et al., 2018). **(B)** MRF absorber with center drain hole (Li Z. Q. et al., 2018). **(C)** Outer multi-pole MRF damper (Liu et al., 2018). **(D)** Internal bypass MRF absorber (Bai et al., 2018). **(E)** MRF damper with permanent magnet (Lee et al., 2018).

magnetization of MRF is not uniform. In addition, MRF after magnetization and the permanent magnets are magnetically attractive, thus a large force is required to separate them. To improve durability, a magnetic screw pump was studied to promote fluid mixing within an MRF clutch, shown in **Figure 6C** (Pilon et al., 2020). Instead of having solid flights, the screw flights are made of 3D structures of MRF formed by the concentration of the magnetic field lines around helical grooves. From durability test results, the specific structure can increase durability by up to 42% when compared to a standard MRF based clutch.

MAGNETORHEOLOGICAL FLUID DAMPERS AND MOUNTS IN ENGINEERING APPLICATIONS

As a new type of mechanical device, MRF dampers and mounts have the ability to provide variable damping (Xu et al., 2018b), mitigate adverse vibration (Dong et al., 2018), and recycle kinetic energy (Wang et al., 2018), and play a key role in many fields (Ha et al., 2018; Lv et al., 2020). For different engineering applications, the development of high-performance MRF dampers and mounts has always been a research hotspot, such as adjusting local structure size, optimizing internal magnetic field, and updating configuration design.

In 2018, based on the concept of functional integration, an MRF device was proposed with controllable damping, energy recovery, and velocity self-sensing, shown in **Figure 7A** (Bai et al., 2018). In this device, a damping mechanism with MRF generates torque, which is then translated to a linear damping force *via* a ball screw. Cooperating with a permanent magnet rotor and generator stator, the ball screw converts the mechanical energy to an electrical energy for storage or directly to power electromagnetic coils. To reduce harmfulness from an overshoot to a buffered object, an MRF energy absorber, as a controllable damper, was presented and is shown in **Figure 7B** (Li Z. Q. et al., 2018). In the device, a structure configuration of a central drain hole is designed on the inner plate to share the drop pressure of MRF and cannot be affected by the magnetic field. However, the design forms a straight flow channel of MRF, which limits the increase of the damping force. To have a better vibration isolation effect, an MRF damper was designed by utilizing multiple electromagnetic poles integrated in the cylinder, shown in **Figure 7C** (Liu et al., 2018). In the MRF damper, the magnetic flux density in the annular flow channel is effectively increased compared with that of the traditional channel, and the multi-pole structure could minimize the dimension of the piston to improve the active area for a great dynamic range of the damping force. Although the device reduces the volume of the piston and MRF, it increases the size and number of coils, and does not decrease the overall weight. Furthermore, an internal bypass MRF shock absorber was proposed for vibration control of high-speed, and is shown in **Figure 7D** (Bai et al., 2019). The MRF device consists mainly of the inner and outer coaxially arranged cylinders and one piston. Five electromagnetic coils wound on the outer wall of the inner cylinder increase work length of the fluid gap, and the decoupling windings from the piston effectively improve the stroke of the damper. As the inner cylinder is constrained mainly by the MRF and piston, when the center of inner cylinder is shifted from the axis of the device, the movement of the piston rod may be affected, and the outer cylinder can be damaged. Moreover, to optimize the response time of the damper, an MRF damper with a

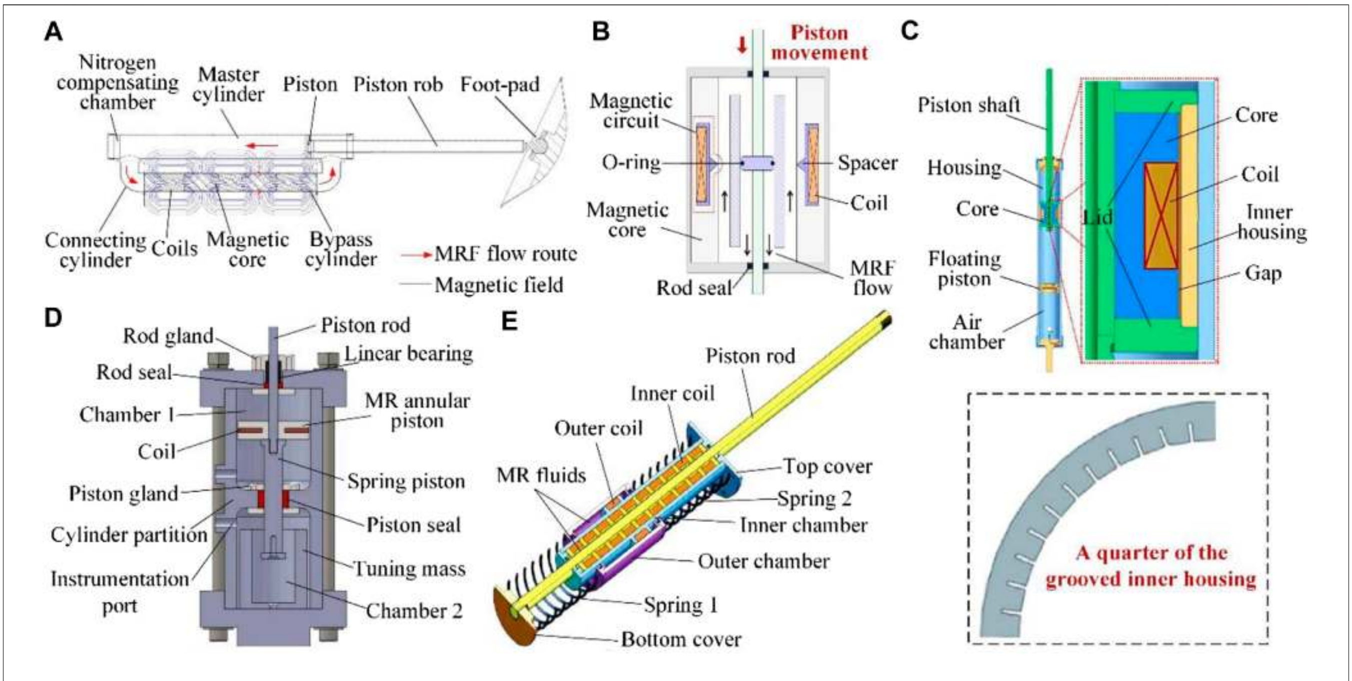

FIGURE 8 | (A) MRF damper with combination structure (Wang C. et al., 2019). **(B)** MRF damper with pinch mode (Lee et al., 2019). **(C)** MRF damper with fast response (Yoon et al., 2019). **(D)** Bi-directional liquid spring MRF damper (Maus and Gordaninejad, 2019). **(E)** MRF damper with two chamber damping units (Deng H. X. et al., 2019).

permanent magnet was proposed, and is shown in **Figure 7E** (Lee and Choi, 2019). Using ferromagnetic and paramagnetic sidebars shaped by a rectangular column, the step input of the damping force is achieved by the structure design of the magnetization area.

In 2019, an MRF damper, shown in **Figure 8A**, was proposed for the lunar lander, which can absorb the impact energy from complex landing surfaces (Wang C. et al., 2019). In the device, a combined structure of master and bypass cylinders is designed, where the master cylinder is connected with the piston rod to receive the external impact; the bypass cylinder with coils adjusts the flow viscosity of MRF to change damping. Thus, the MRF in the damper has a definite flow circuit, and damping control is reliable. Furthermore, an MRF damper with a pinch mode was proposed, where a triangle-shaped nonmagnetic spacer is designed to separate the magnetic core and to generate undulating magnetic field lines, shown in **Figure 8B** (Lee et al., 2019). Utilizing the magnetic field circuit, a pinch mode is formed in the annular MRF damper, and the pinch effect is verified in experiments. To realize a fast response, an MRF damper was designed and is shown in **Figure 8C** (Yoon et al., 2019; Yoon D. S. et al., 2020). A soft magnetic composite is selected as the core material and the inner surface of the housing is machined with grooves. Through these improvements, the eddy current effect on response time is reduced in the MRF device. In addition, a bi-directional liquid spring damper with MRF was presented and is shown in **Figure 8D** (Maus and Gordaninejad, 2019). The device with a two-chamber design has equal or dissimilar spring rates in compression and rebound, and the spring rate can also be pre-set independently in both compression and rebound. Because of the two-chamber structure, the sealing area of MRF needs to be increased relatively. Based on the combined operation mode, MRF dampers with an inner and outer chamber damping units were presented (Deng H. X. et al., 2019; Huang et al., 2019). The inner chamber damping unit is connected to a vibrating object, while the outer is connected to a spring, and is shown in **Figure 8E**. Specifically, the inner unit is set as the piston rod of the outer unit, and outer coil is wound around the outer wall of the inner unit. The combined operation mode effectively expands the control range of the damping force and the stroke range of the piston rod. However, as the damping force is regulated jointly by the spring and MRF, the accurate output of the device is more complicated.

In 2020, aiming to reduce the sedimentation of MRF, a damper shown in **Figure 9A** was designed (Huang et al., 2020). In this device, a permanent magnet is embedded in the piston to drive particles back and forth, and a conductive strip is disposed to monitor particle chains of MRF for a sedimentation amount. On the other hand, the permanent magnet also enhances the resistance of the piston during normal movement and increases the energy consumption. To realize a huge range change of the damping force, an MRF damper with a squeeze and valve mode was presented, and is shown in **Figure 9B** (Ruan et al., 2020). In this device, the piston has an internal channel that divides MRF into three parts. With the movement of the piston, MRF has squeeze and valve working modes at the same time. Furthermore, a bypass MRF damper was proposed with a serpentine flux valve type, and is shown in **Figure 9C** (Idris et al., 2020). The valve of MRF is connected to a cylinder in the

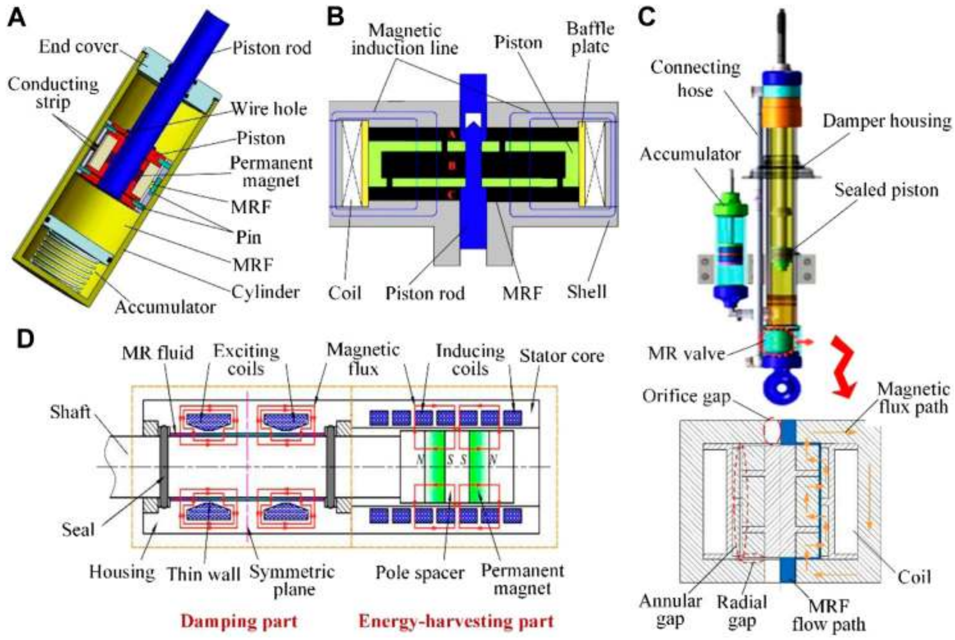

FIGURE 9 | (A) MRF damper with self-monitoring (Huang et al., 2020). **(B)** MRF damper with squeeze-valve mode (Ruan et al., 2020). **(C)** MRF damper with serpentine flux valve (Idris et al., 2020). **(D)** MRF damper with self-powered (Bui et al., 2020).

same center axis but is not attached to the piston. So, the device has a larger dynamic range and is less bulky than conventional structures. Moreover, to reuse vibration energy and to simplify the structure, a self-powered MRF damper was proposed for washing machines (Bui et al., 2020). The device integrates an energy-harvesting technology, where induced power from induction coils is directly transmitted to excitation coils of the damper to generate a corresponding damping force, as shown in **Figure 9D**.

In addition, some other MRF dampers, mounts, and absorbers with a vibration reduction effect have been studied and optimized in key positions to effectively improve the working performance. These MRF devices are also summarized for corresponding improved methods, as shown in **Table 3**.

MAGNETORHEOLOGICAL FLUID BASED DEVICES IN MEDICAL APPLICATIONS

With the development of remote surgery and robot-assisted equipment, the MRF plays an increasingly important role in the medical field. The MRF is mainly applied in two aspects—tactile feedback devices and medical wearable rehabilitation devices. The research results obtained between 2018 and 2020, are briefly summarized in **Table 4**.

Using MRF to simulate the feedback of different environments and to provide operators with real tactile experience are currently hot research topics. In 2018, for surgical robotic applications, a force generator module with MRF was developed to provide force-feedback information (Shokrollahi et al., 2020). The device, shown in **Figure 10A**, is capable of rapidly re-producing forces generated in tele-robotic bone biopsy procedures and provides a wide range of force measurements. However, it is difficult to simulate all the stress ranges only using MRF in the areas where the hardness changes greatly between bone and soft tissue. In 2019, an MRF spherical actuator with haptic feedback was proposed to the applications of joysticks (Chen D. P. et al., 2019). The actuator, shown in **Figure 10B**, has a special stator that replaces the traditional single coil with eight separate coils and magnetic circuits, which can achieve control of forces in different interaction directions. Furthermore, an endovascular catheterization system shown in **Figure 10C** was proposed, which consists of a master device and a slave device (Yin et al., 2018; Guo et al., 2019). In the slave device, the catheter moves in the blood vessel and sends real resistance obtained by the sensor to the master device. The master device uses MRF to simulate the resistance, thus giving the remote physician a realistic sense and improving the safety of surgery. This master device provides an approximate damping environment, but in a particular direction, the variation of damping is not very differentiated. Similarly, to realize a certain stiffness and damping properties of human tissue, a controllable tactile device was designed, where MRF was immersed into porous polyurethane foam and sealed by adhesive tape (Park et al., 2020). The device, shown in **Figure 10D**, can capture several different repulsive forces of human organs generated at an operating site in minimally invasive surgery and can improve the real tactile sensing of the remote doctor.

Moreover, MRF also has many new applications in medical rehabilitation equipment. In 2018, a prosthetic knee with a novel MRF brake was proposed, assisting humans to realize normal gait movement (Mousavi and Sayyaadi, 2018). The MRF brake,

TABLE 3 | Other MRF dampers, mounts and absorbers in 2018–2020.

No	References	Type	Improved method
1	Xin et al. (2018)	Piston type damper with shear-flow mode	Presenting a double-ended damping structure to reduce the random vibration of pipeline
2	Chen C. et al. (2018)	Piston type damper with flow mode	Converting wasted mechanical energy into useful electrical energy to power damper itself
3	Urkucu and Keles (2018)	Mount with flow mode	Comparing two decoupled plates with slots and holes in MR mount
4	Deng et al. (2018)	Non-piston type damper with shear mode	Replacing piston with a suspension rod and realizing unlimited work stroke
5	Xu et al. (2018a)	Piston type damper with flow mode	Utilizing two dis-springs to re-left itself
6	Cheng et al. (2018)	Piston type damper with flow mode	Using meandering magnetic circuit to improve damping performance
7	Sassi et al. (2018)	Piston type damper with flow mode	Placing excitation current and magnetic field outside the damper
8	Yang et al. (2019)	Piston type damper with flow mode	Adding an aluminum slider to reduce the unbalance of damper rod and avoid magnetic leakage
9	Ning et al. (2019)	Rotor type damper with shear mode	Proposing a variable admittance concept
10	Oh and Choi (2019)	Piston type damper with flow mode	Comparing two different dampers, with and without orifice holes in the piston
11	Chen B. et al. (2019)	Two-dimensional plate type damper with shear mode	Optimizing structure design parameters
12	Zhang J. L. et al. (2019)	Disc type damper with shear mode	Utilizing the coil with trapezoidal cross section to improve magnetic field distribution
13	Christie et al. (2019a)	Disc type damper with shear mode	Optimizing structure design parameters
14	Ouyang et al. (2019)	Piston type damper with flow mode	Adopting multi-stage parallel coil structure to realize various magnetic field variations
15	Desai et al. (2019)	Piston type damper with flow mode	Optimizing magnetic field of twin-tube structure
16	Han et al. (2019)	Piston type damper with flow mode	Investigating different pole length and different number of magnetic cores
17	Qiang et al. (2019)	Disc type damper with shear mode	Using ultrasonic field to reduce the angular momentum losses of device without magnetic field
18	Deng L. et al. (2019)	Combined dampers with shear mode	Assembling drum-type damper and disc-type damper
19	Kim et al. (2020)	Piston type damper with shear mode	Utilizing ferromagnetic and paramagnetic materials to adjust damping coefficient
20	Kang et al. (2020)	Piston type damper with flow mode	Optimizing structure design parameters
21	Zhong et al. (2020)	Integrated shock absorber with flow and shear mode	Combining inerter, damper and spiral spring to realize adjustable inertance and damping characteristics
22	Wei et al. (2020)	Blade valve type damper with flow mode	Combining blade and two MR valves with parallel plate damping channel in compact structure
23	Zareie et al. (2019), Zareie and Zabihollah (2020), Zareie et al. (2020)	SMA MRF type damper with flow mode	Proposing a structural control element for high performance of control system
24	Zhang X. J. et al. (2020)	Piston type damper with squeeze mode	Integrating the characteristics of pumping hydraulic damper and MR valve with squeeze mode
25	Elsaady et al. (2020b)	Piston type damper with flow mode	Optimizing magnetic field distribution
26	Zhao et al. (2020)	Piston type damper with flow mode	Integrating four axial fan-shaped magnetic poles on magnetic core to enhance output performance

TABLE 4 | Main applications of MRF in the medical field in 2018–2020.

No	References	Application
1	Shokrollahi et al. (2020)	Robotic bone biopsy device with haptic feedback
2	Chen D. P. et al. (2019)	Multi-direction spherical actuator for haptic applications
3	Guo et al. (2019)	Endovascular catheterization system with haptic force feedback
4	Park et al. (2020)	Simulated human tissues with controllable tactile forces
5	Mousavi and Sayyaadi (2018)	MRF brake with drum of arc form surface for prosthetic knee
6	Wahed and Balkhoyor (2018)	Prosthetic joints with MRF damper of ball-and-socket structure
7	Chen Z. P. et al. (2018), Chen et al. (2019a, 2019b)	Microneedle arrays for minimally invasive surgery, transdermal drug delivery and smart wearable equipment
8	Oba et al. (2019)	Semi-active ankle-foot orthosis with MRF link mechanism
9	Christie et al. (2019b)	Prosthetic leg with MRF damper of T-shaped drum
10	Zahedi et al. (2020)	Soft exoskeleton with MRF damper to suppress pathological tremor

shown in **Figure 11A**, has a T-shaped drum with an arc form surface boundary, which can meet the requirements for flexible variation of the braking torque. To enhance the rehabilitation of the human shoulder and upper limb, a multi-freedom MRF based damper with a ball-and-socket structure was proposed (Wahed and Balkhoyor, 2018; Wahed and Wang, 2019). The new damper shown in **Figure 11B** can effectively simulate the motion of human joints and provides a rehabilitation training environment. Further, the device can refine the design of damping forces in different directions to realize the control of damping variation in

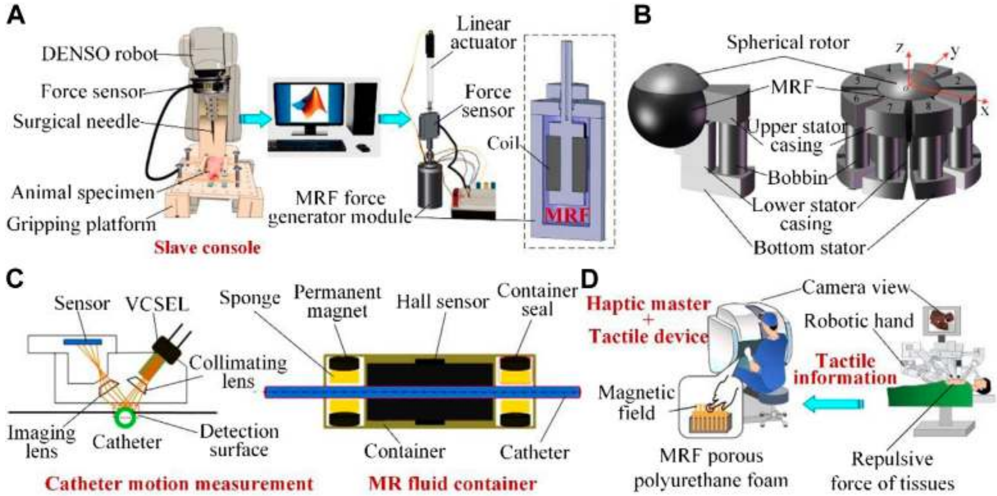

FIGURE 10 | (A) MRF haptic device for robotic bone biopsy (Shokrollahi et al., 2020). **(B)** Multi-direction MRF actuator for haptic applications (Chen D. P. et al., 2019). **(C)** Endovascular catheterization system with haptic feedback (Guo et al., 2019). **(D)** Tactile device to simulate human tissues forces (Park et al., 2020).

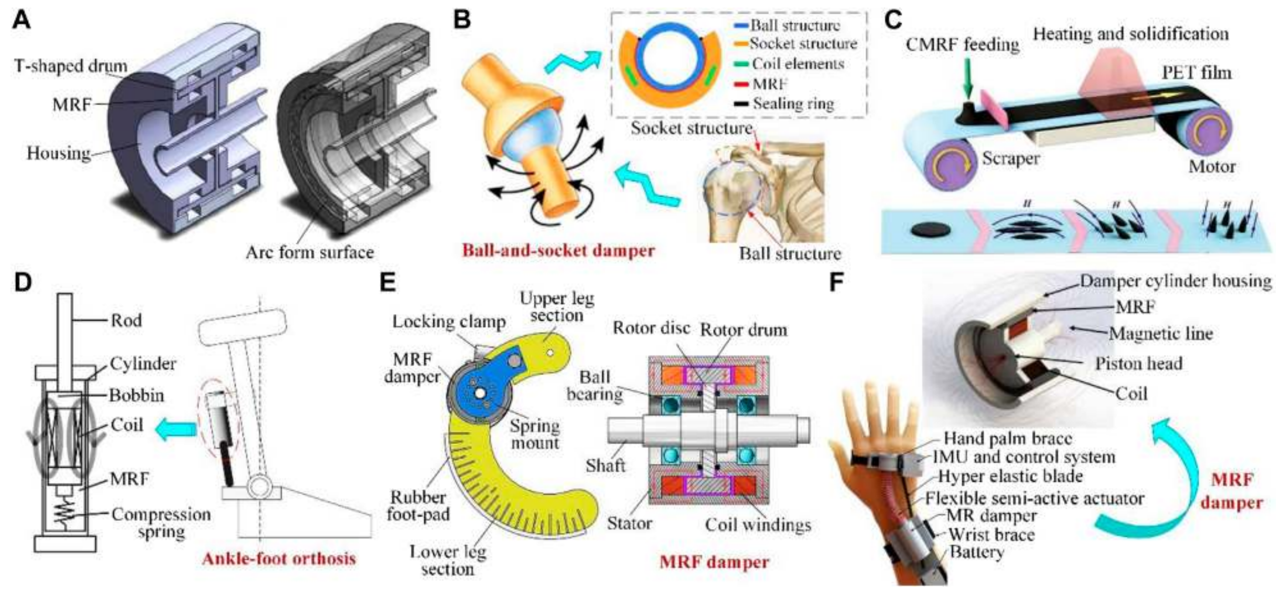

FIGURE 11 | (A) MRF damper with drum of an arc surface boundary (Mousavi and Sayyaadi, 2018). **(B)** Smart ball-socket actuator for upper limb rehabilitation (Wahed and Balkhoyor, 2018). **(C)** Magnetization-induced self-assembling process of microneedle array (Chen Z. P. et al., 2018; Chen et al. 2019a; Chen et al., 2019b). **(D)** MRF damper for ankle-foot orthosis (Oba et al., 2019). **(E)** MRF based variable stiffness leg (Christie et al., 2019b). **(F)** MRF soft exoskeleton (Zahedi et al., 2020).

multi-directions. Furthermore, using a drawing lithography approach, some MRF microneedles were fabricated for minimally invasive surgery, transdermal drug delivery, and smart wearable equipment (Chen Z. P. et al., 2018; Chen et al. 2019a; Chen et al., 2019b). In a gradient magnetic field, the MRF is magnetized and generates fusiform patterns, which results in different forms of microneedle arrays after heating and solidifying, as shown in **Figure 10C**. The MRF microneedles are cheaper and simpler to produce than traditional precision machining. With the aim to prevent paralysis and gait abnormalities affecting human ankle joints, a semi-active ankle-foot orthosis with an MRF link mechanism was designed (Oba et al., 2019). The MRF device, combined with a compression spring, can mitigate foot slap and toe drag during different phases of movement, as shown in **Figure 11D**. Similarly, for movement recovery, an MRF variable stiffness leg was designed to improve energy efficiency and gait stability (Christie et al., 2019b). The device, shown in **Figure 11E**, is housed in the lower leg section, whose output shaft is linked to the upper leg section. When the coil current is zero, the leg has a soft single spring stiffness, while huge damping torque is achieved under a large input current. Therefore, the device has a relatively wide range of damping variation. Moreover, based on the assistive technologies, a novel soft exoskeleton with MRF damper was proposed to suppress pathological tremor (Zahedi et al., 2020). The MRF damper connected with a flexible elliptic spring can assist in suppressing tremor of the wrist joint in 3° of freedom with varying intensity, as shown in **Figure 11F**. This device prevents wrist tremor with a less constrained area on the hand surface, which thus reduces the suppression effect of a small amplitude tremor.

CONCLUSION AND PROSPECTIVE

According to different structure configurations, MRF based devices reported from 2018 to 2020 are investigated in this work, including MRF brakes, MRF clutches, MRF dampers and mounts for engineering applications, and other new devices for medical applications. In terms of the literature presented above, improvement methods are mainly concentrated in the following ways: Use of multiple coils or magnetic poles to enhance magnetic field strength; Improving the combination of braking structure and active structure to increase the effective contact area of MRF; Replacing the coil with a permanent magnet, or adjusting the size and position of the permanent magnet to improve working performance; Optimizing the magnetic circuit to improve the utilization ratio of the magnetic field; Changing the position of the magnetic field in the working process to avoid settling of MRF or reducing the zero field viscosity. There have been many successful applications that have come from these improvements, but some problems still need to be addressed. By adding coils and magnetic poles, the volume and weight of devices can be larger, which is not easy to disassemble and cost may also be increased. Furthermore, when the working area of MRF is enlarged, the wear is relatively enhanced and the working temperature is also increased, so the rheological property is decreased. By adopting a bypass or extension structure, the output range of devices is extended, but the response time and maximum output force needs to be balanced. In addition, when the MRF is applied in haptic devices, it is still limited to simulating the feedback forces that are in different directions at the same time or one direction with large variation gradient.

In light of the practical application requirements, some development directions are proposed for MRF based devices. The combination of working modes in a limited volume may play a greater role, such as shear-squeeze mode, flow-squeeze mode, etc. The cooperation of magnetic materials and coils can be further developed to increase strength, flexibility, and utilization of the magnetic field, and can reduce power consumption. In order to improve the service life of devices and the accuracy of fault diagnoses, some structure can be designed to measure the working temperature and wear condition of MRF. With the increasing torque output, the energy loss caused by zero field viscosity should be seriously considered, where an ultrasonic wave can be used to reduce zero field viscosity or can cut off the contact between MRF and the rotor to avoid unnecessary energy consumption. Aiming to improve the accuracy of haptic feedback in complex structures, MRF can be combined with other rheological materials or magnetic actuated elastic materials to design a multilayer configuration.

The application potential of MRF in different fields will be further explored. For example, according to the variable damping and stiffness characteristics of MRF, intelligent wearable devices can be used in medical treatment to prevent joint vibration; in virtual reality devices, the motion damping is changed for the wearer to increase the experience of a real environment; in the remote control of medical or other fields, real-time tactile feedback is simulated for operators to improve the sense of reality. Although these directions present many challenging problems, the need for practical applications will certainly drive current research of MRF based devices forward.

AUTHOR CONTRIBUTIONS

DH: Methodology, software, data curation, writing-original draft preparation. XL: Conceptualization, methodology, analysis. ZL: Resources, visualization, investigation. PF: Analysis, writing-reviewing and editing. AH-S: Resources, funding acquisition, writing-reviewing and editing. ZL: Conceptualization, writing-reviewing and editing, funding acquisition.

FUNDING

This work was supported in part by the Future Scientists Program of China University of Mining and Technology (2020WLKXJ025), the Postgraduate Research and Practice Innovation Program of Jiangsu Province (KYCX20_1986) and Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.