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Review:

A review of advances in magnetorheological dampers: their design optimization and applications*

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Abstract: In recent years, magnetorheological (MR) fluid technology has received much attention and consequently has shown much improvement. Its adaptable nature has led to rapid growth in such varied engineering applications as the base isolation of civil structures, vehicle suspensions, and several bio-engineering mechanisms through its implementation in different MR fluid base devices, particularly in MR dampers. The MR damper is an advanced application of a semi-active device which performs effectively in vibration reduction due to its control ability in both on and off states. The MR damper has the capacity to generate a large damping force, with comparatively low power consumption, fast and flexible response, and simplicity of design. With reference to the huge demand for MR dampers, this paper reviews the advantages of these semi-active systems over passive and active systems, the versatile application of MR dampers, and the fabrication of the configurations of various MR dampers, and provides an overview of various MR damper models. To address the increasing adaptability of the MR dampers, their latest design optimization and advances are also presented. Because of the tremendous interest in self-powered and energy-saving technologies, a broad overview of the design of MR dampers for energy harvesting and their modeling is also incorporated in this paper.

Key words: Magnetorheological (MR) fluid dampers; Vibration control; Self-powered review; Energy saving; Optimization and advancement
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1 Introduction

A vibration control system reduces unwanted vibration of civil structures or of vehicle bodies from road shocks, vibrations, and earthquakes which would otherwise be shifted to passengers, load or inhabitants of the buildings. Thus, a vibration control system increases passenger safety and provides ride comfort. Different types of devices are used as vibration insulators and among them the damper is prominent. Usually the selection between three types of dampers, passive, active, and semi-active, is implemented according to need. Most dampers used today are passive in nature, though such dampers have many limitations. A passive damper only dissipates energy from the system. In a passive suspension system, the characteristics of the dampers are static and determined by designers considering design goals and the envisioned application. An active suspension, on the other hand, consists of sensors, controllers, and active actuators controlled by feedback signals, springs, etc. The force actuator of an active suspension system has the ability to add energy to, or dissipate energy from, the system. The applied force of this force actuator

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does not depend on the relative displacement or velocity through the suspension. A combination between a passive system and an active suspension system is the semi-active suspension system which retains the spring element from the conventional passive system and also uses a controllable damper (which is similar to the actuator) from the active system. An external energy source in the semi-active damper is only needed to adjust the damping level. In a power failure, it works as a passive damper and thus has continuous controllability in both on and off states of power. In a passive suspension system, design and construction cannot be changed after installation, but that can be done easily in semi-active suspensions. Overall, there are thus some real improvements and advantages in semi-active dampers as compared to passive and active dampers. The magnetorheological (MR) damper is one of the advanced applications of semi-active devices, and a semi-active system based on it is shown schematically in Fig. 1.

The semi-active system presented in Fig. 1 contains two controllers, the damper controller and the system controller. The preferred damping force for the damper controller is generated by the system controller in accordance with the system's dynamic responses. The damper controller controls the MR damper by providing the necessary current (i) to the damper through adjustment of the command voltage to the current driver and consequently the MR damper delivers a controlled damping force to the plant. Design and applications of the above-mentioned three control strategies are well described in different studies (Ou and Li, 2009; Fisco and Adeli, 2011; Casciati *et al.*, 2012; Ma *et al.*, 2016).

Zhu *et al.* (2012) and Kumbhar *et al.* (2015) presented MR fluid characterization, synthesis, and its application. An MR damper contains a type of smart fluid called a magnetorheological fluid (MRF). Changes in the applied excitation current vary the strength of the magnetic flux density of the electromagnets and consequently vary the rheological properties of the MR fluid. Such fluids contain micron-sized magnetic particles (5–50 μm) such as iron, suspended in a carrier fluid, usually a kind of oil. Without an applied magnetic field, the MRF behaves as a conventional fluid and its viscosity is independent of the flow rate. However, the application of a magnetic field creates a dipole moment aligned to the field in the iron particles, and the particles form linear chains parallel to it, as shown in Fig. 2.

Usually the MRF contains 20%–40% by volume of pristine soft iron particles, mixed with mineral oil, synthetic oil, water, or glycol. Various additives are usually included to minimize the settling problem of iron particles, enhance lubricity, modify viscosity, and inhibit wear (Yang, 2001; Newton, 2009). One of the major and most important applications of MRF is in the development of MR dampers.

An MR damper is a semi-active device which generally consists of a damper housing, piston shaft, inner and outer pistons, piston guide, floating piston, MRF, and gas chamber. It has numerous advantages such as a large viscosity control range, relatively low price, low power feeding, quick response, and small size. In this device MRF is used and its viscosity changes very quickly with the applied magnetic field, moving to semi-solid from liquid in only a few milliseconds. It results in an enormously variable

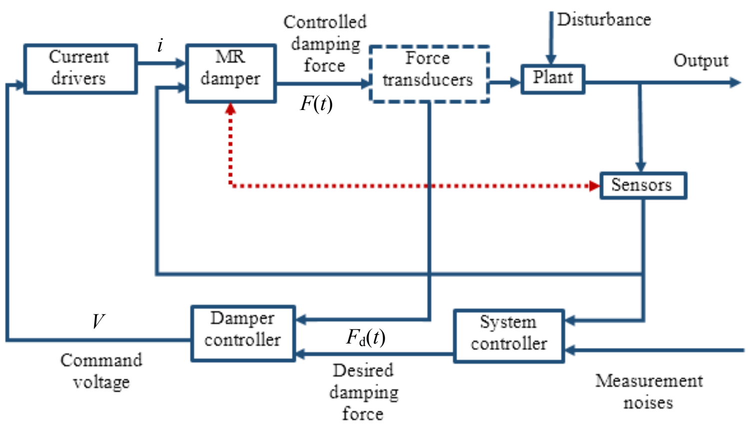


Fig. 1 Schematic diagram of a semi-active system based on an MR damper

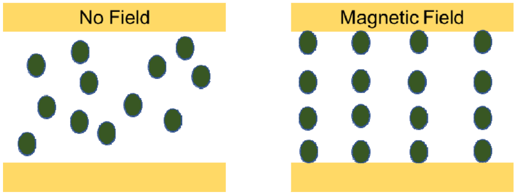


Fig. 2 MRF magnetic particles chain-like formation with applied magnetic field

and controllable damper able to provide a large resisting force (Jiang *et al*., 2011; Ferdaus *et al*., 2014a; Togun *et al*., 2014). Because of the nonlinear behavior of the MR damper, it is important to develop a suitable controller for it to achieve maximum force with minimum power supply. Various MR damper controllers have been proposed and implemented, and some effective and well-known control strategies are presented (Jansen and Dyke, 2000; Cha and Agrawal, 2013a; 2013b; Cha *et al*., 2013a; Mitchell *et al*., 2013). In these studies, current/voltage inputs were controlled based on the vibration amplitude level. This is unique feature of a semi-active control system where the minimum power supply can be applied and save power. To obtain the full advantage of the unique features of the MR fluid damper and its nonlinear behavior, proper models must be developed that effectively depict the behavior of a typical MR damper. Different MR damper models have been proposed and the responses of the MR dampers are analyzed (Dyke *et al*., 1996; 1998; Spencer *et al*., 1997; Qian *et al*., 2016). In these studies, experimental analysis was investigated and compared with a simulated response to evaluate the performance of the models. The applications of MR damper models (mainly for vehicle suspension systems) were also presented. There are also various types of developed models for the characteristics of MR dampers. According to the method of modeling, the models are classified as parametric (Wang and Liao, 2011) and non-parametric dynamic models (Ehrgott and Masri, 1992; Choi *et al*., 2001; Jin *et al*., 2005; Song *et al*., 2005; 2007; Kim *et al*., 2008). By considering the characteristics shown by the established models, they can be further classified as quasi-static models (Phillips, 1969; Gavin *et al*., 1996; Kamath *et al*., 1996; Makris *et al*., 1996a; 1996b; Wereley and Pang, 1998; Lee and Wereley, 1999; Wang and Gordaninejad, 2000; Dimock *et al*., 2002; Lee *et al*., 2002; Choi and Wereley, 2005; Chooi and Oyadiji, 2008; 2009a; 2009b; Hong *et al*., 2008a; 2008b) and dynamic models. Considering the reversibility of the established models, they can be classified as dynamic models (Wang and Liao, 2005; 2011) and inverse dynamic models (Tsang *et al*., 2006).

A major application of dampers is in vehicle suspension systems (Rashid *et al*., 2011). The wasted energy from road vibration is related to highway roughness, car speed, a rigid passive suspension system, and its damping coefficient (Velinsky and White, 1980; Crolla and Nour, 1992). Segel and Lu (1982) and Fodor and Redfield (1993) reported that the total power dissipated by the four dampers of a vehicle reached 200 W while travelling on a rough highway at a speed of 13.4 m/s. External power supply would not be needed if that wasted energy were transformed into electrical energy (Scruggs and Iwan, 2003; Lesieutre *et al*., 2004; Atabani *et al*., 2012), and by measuring the dynamic responses no extra sensor would be required. This concept of the self-sensing and self-powered damper has been used to develop an energy-saving smart MR damper. The technology has no harmful effects on the environment and has improved the credibility of whole MR damper systems. Massive advantages of the system are reduced weight and size, low maintenance costs, and controllability, which is very beneficial under some extreme conditions such as earthquakes when the power supply may be cut off. Nakano *et al*. (2003) observed that producing energy in the regenerative process helps to fulfill the energy demand in the dampers. Hsu (1996) measured the total regenerative power, which reached 100 W when travelling at 16 m/s. Yu *et al*. (2005) compared the energy dissipated in both passive and active suspensions of a vehicle. Following the former research on self-sensing controllable dampers, an integrated magneto stricture position sensor was developed for MR dampers (Russell, 2001). It was difficult to develop commercially due to its complicated structure, manufacturing requirements, and costly magneto stricture materials. Nehl *et al*. (1996) proposed an integrated self-energizing comparative velocity sensor which is impossible to center within MR dampers. The coil of the sensor is wound on the dust tube of the MR dampers with resultant performance degradation of the sensor and thus limiting its use in MR dampers.

Some researchers introduced an MR damper based on electromagnetic induction (EMI) and combined it with a similar displacement sensor (Wang and Wang, 2009; Wang *et al*., 2010; Wang and Bai, 2011). This sensing process consisted of complicated circuits for signal processing. Or *et al*. (2008) presented an MR damper including a piezoelectric force sensor. Some research has been done on the power generation ability of an MR damper such as that in (Cho *et al*., 2005) where the authors introduced an MR damper with power regeneration capability consisting of an EMI device for reducing suspension vibrations. It shows a route to self-powered vibration control and the EMI exploits vibration energy to produce electrical energy, but its large size has made it inapplicable in confined environments, such as cars, buses, motorcycles, and robots. Choi and Wereley (2009) described some corresponding research. They studied the liability and effectiveness of a self-powered MR damper and used a spring-mass EMI device. They used the energy produced as the source of MR damping directly thus avoiding the use of the accessory sensors used in the previous two works. However, it is inappropriate for some applications as the control algorithm is fixed. Sapiński (2010) demonstrated a power generator for a linear MR damper called an electromagnetic power generator. This research focused mainly on the performance and construction of the generator. All this research on self-sensing or power generation MR dampers has shown useful results. However, little research has been done on MR dampers that integrate sensing ability and power generation in the same device. Chen and Liao (2012) proposed a self-sensing and self-powered MR damper. Their design is developed for a double-ended MR damper and is applicable to civil engineering structures.

The great advantages of the MR damper widen its range of application. It is used in the suspensions of heavy duty trucks and other road vehicles (Sung *et al*., 2011; Du *et al*., 2013; King, 2013; Xie *et al*., 2013), in a seat suspension system where it is known as motion master (Du *et al*., 2011; 2013; Laalej *et al*., 2012), in haptic devices (Tsujita *et al*., 2012), in knee prosthetics of limbs to control the force (Gudmundsson *et al*., 2010; Xie *et al*., 2010), in civil structures (Bitaraf *et al*., 2012; Cha *et al*., 2013b; El-Khoury and Adeli, 2013), in military equipment (Singh and Wereley, 2014), in fixing turning devices to hold turbine blades while they are being machined (Johnson and Kienholz, 1982), in wind turbines (Rahman *et al*., 2015), in landing gears (Powell *et al*., 2013; Atabay and Ozkol, 2014), in helicopter lag dampers (Kothera *et al*., 2011), and in aerospace launching applications (Jean *et al*., 2005). This versatile applicability requires researchers to work on the optimization of the design and configuration of dampers, and to optimize them with respect to their specific applications.

In this study, different designs and configurations, modeling, optimization, and advancement in design and fabrication of MR dampers, especially in respect of their energy harvesting capability are presented comprehensively to help understanding of the rapid growth of demand for MR dampers. Extensive literature reviews on famous and recent journal papers and books have been prepared on MR fluid technology (Goncalves, 2005; de Vicente *et al*., 2011), application of MR dampers, various design configurations and modeling of MR dampers over the last two decades, and advanced design optimization considering various parameters, and more broadly on self-powered and self-sensing smart MR damper design and modeling (Choi and Wereley, 2009). Overall, the possibilities for implementing MR dampers for various purposes require an assessment of present designs and configurations, and of the advantages, limitations, improvements, and optimizations for MR dampers in future to ensure more adaptability and reliability. Therefore, this paper focuses on all aspects of MR dampers, including applications, design and configurations, implementations in various structures as well as potential improvements in them.

2 Existing design, construction, and classification of MR fluid damper

Conventional shock absorbers inspire the design of the MR damper. It is a semi-active damper which has the ability to control the input current for control. It generally consists of a damper housing, a piston shaft, inner and outer pistons, a piston guide, a floating piston, MR fluid, and a gas chamber as shown in Fig. 3. Inside the damper housing piston guides contain the outer piston. The inner piston is surrounded by the outer piston, with a small gap between them for the MR fluid to flow. The coil is housed inside the inner piston in such a way that its induced magnetic flux can flow through the MR fluid. This magnetic field changes the viscosity of the MR fluid by the alignment of magnetic particles as shown in Fig. 4 and thus changes the force required to move the piston through the MR fluid. As the current increases, the induced magnetic field strength increases, and a greater force is required to move the piston. The combination of these inner and outer pistons, piston housing, and coil form an MR valve structure.

From the structure, it is seen that this MR valve divides the damper into two chambers, the lower and upper chambers, fully filled with the MR fluid. The maximum force delivered by magnetorheological damper (MRD) is governed by the properties of the MRF, its flow mode, and the size of the MRD. Practically all devices that use MRF are categorized as functioning in three modes: valve mode, direct shear mode, and squeeze mode. When an MR damper operates in valve mode, the MRF itself hinders the MRF flow from one reservoir to another and it is the most commonly used mode among the three modes for an MR damper as shown in Fig. 5a (Spencer *et al.*, 1998). MRF devices are operating in shear mode when a thin layer of MRF is sandwiched between two paramagnetic moving surfaces shown in Fig. 5b. The shear mode is primarily beneficial for dampers those can provide small forces, such as for compact clutches and brakes. An MRF device is said to be operating in squeeze mode when a thin film (of the order of 0.0005 m) of MR fluid is sandwiched between pole surfaces as in Fig. 5c. The most recent MRF flow mode is known as the magnetic gradient pinch mode, which is similar to the MRF valve mode but with a different magnetic construction. In the conventional valve mode, MRF is solidified by a uniform field throughout the valve (Yazid *et al.*, 2014), whereas in magnetic gradient pinch mode the

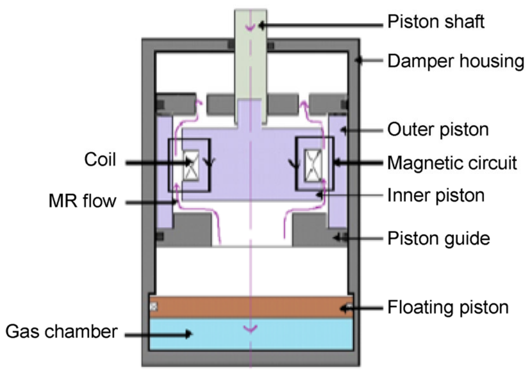


Fig. 3 Typical MR damper configuration

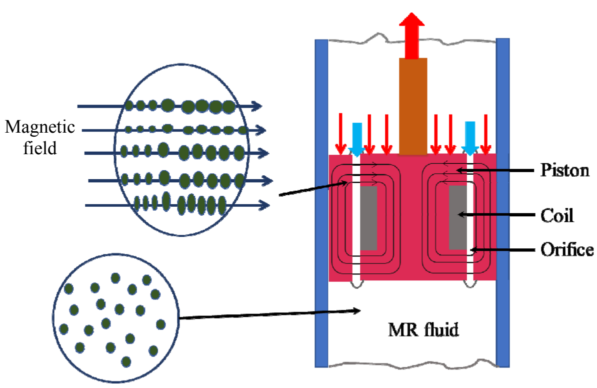


Fig. 4 Basic operating principle of MR dampers

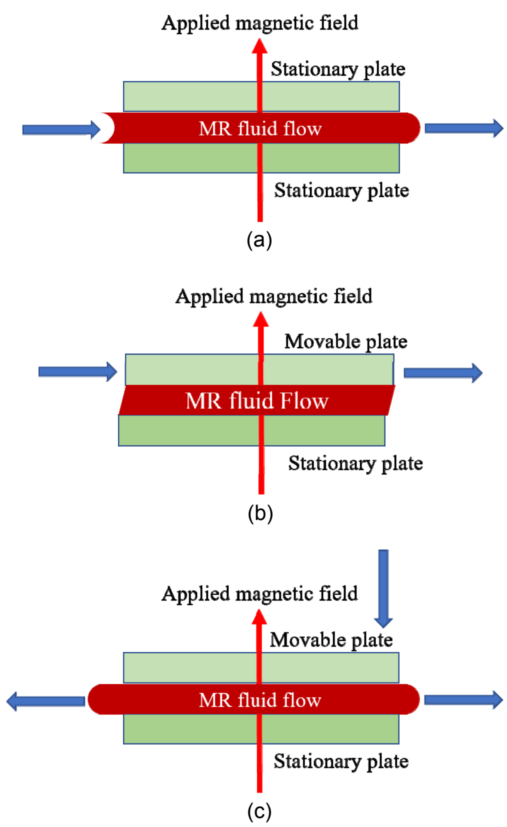


Fig. 5 MR damper modes: (a) valve mode; (b) direct shear mode; (c) squeeze mode

MRF is only solidified near the wall by a non-uniform field. In this mode, the narrow fluid flow path is replaced by a comparatively large opening. In such a configuration the magnetic gradient pinch mode operates in two control modes namely pinch mode and reversible jamming mode.

MR dampers are classified as linear and rotary (Wereley *et al*., 2008) with respect to their piston motion, i.e., when the operation relates to the angular or rotary motion of the piston, they are called rotary MR dampers. In a rotary MR damper, the MRF operates in one or two flow modes integrally. With regard to design and configuration, there are two main types of rotary MR damper, known as continuous angle and limited angle revolution MR dampers (Imaduddin *et al*., 2013). The continuous angle rotary MR damper has the ability to switch with endless rotational angle. The MR brake is a perfect example of a continuous angle MR damper. From the name it is obvious that the MR brake has the ability to reduce the motion of the rotor by altering the MRF viscosity as the rotor is absorbed in MRF. Usually in an MR brake the MRF operates in direct shear mode, whose operation depends upon such factors as magnetic flux density, MRF gap, and working speed. Among these parameters the MRF gap and working speed cannot change after the construction of an MR brake. Thus, the effective way to operate and control this device is to manipulate the magnetic flux density in the activation region. Again with regard to the position of the shear mode, the MR brake is classified as disc type and drum type MR brakes. The designs and operating principles of disc type and drum type brakes are described in (Farjoud *et al*., 2008). In disc type MR brake, shear mode occurs in axial gap of the rotor, whereas for drum type MR brake, shear mode occurs in radial gap of the rotor. On the other hand, a limited angle rotary MR damper, known as the vane type damper, cannot rotate continuously like a continuous angle damper. However, it can produce a larger damping torque compared with the continuous angle damper. Hence, it is appropriate for applications where a high damping torque with limited angular movement is required although it is not suitable for applications that require a high rotor speed. In recent decades, only limited research has been carried out on vane type MR dampers (Giorgetti *et al*., 2010). The overall classification of MR dampers is presented in Fig. 6.

According to the design and configuration of the cylinder of the MR damper, the linear MR damper can be divided into three types: mono-tube, twin-tube, and double-ended MR dampers. Various types of linear damper design, construction, and working principles are summarized in Table 1, with illustrations of the different dampers and their parts also presented.

3 Recent advances and optimization in the design of MR dampers

Research on the design optimization and development of the MR damper is described in (Nguyen

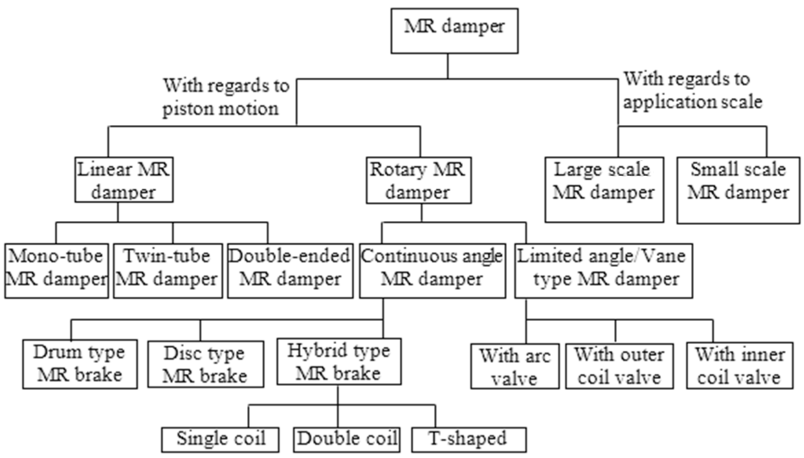
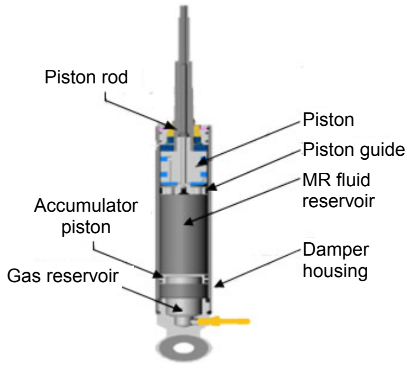
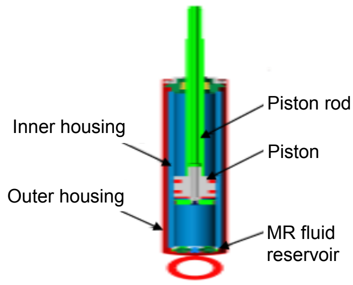
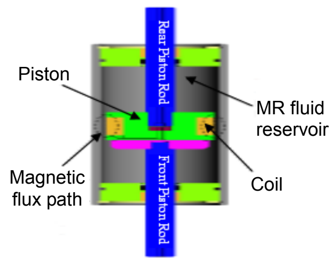


Fig. 6 MR damper classification

Table 1 Linear MR damper designs and working principles

Type of linear MR damper	Design and working principle	Figure
Mono-tube MR damper	This MR damper consists of only one tube or reservoir and is known as a mono-tube MR damper. It is the most commonly used one because of its compact size and ability to be installed in any location. The movement of the piston rod causes a volume change in the reservoir which is compensated for by an accumulator mechanism	 Mono-tube MR damper (Poynor, 2001)
Twin-tube MR damper	An MR damper that contains two fluid reservoirs is called a twin-tube MR damper. For two separate reservoirs this damper has an inner and outer housing. The inner reservoir is filled with MR fluid and there is no air gap. Therefore, the outer reservoir is partially filled with MR fluid to accommodate the fluid of the inner reservoir in times of piston movement. There are two valves in the foot valve mechanism	 Twin-tube MR damper (Poynor, 2001)
Double-ended MR damper	The MR damper in which two piston rods of the same diameter enter the reservoir from both ends of the damper is known as a double-ended MR damper. In this type of damper there is no change of volume due to the piston's relative movement and as a result the accumulator mechanism is absent here. Some common applications of this damper are in gun recoil (Ahmadian and Poynor, 2001), bicycles (Ahmadian *et al.*, 1999), and the control of sway motion in buildings due to heavy winds or earthquakes	 Double-ended MR damper (Poynor, 2001)

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et al., 2008). Nguyen *et al.* (2007) developed an optimized MR valve considering various geometric dimensions by finite element analysis. Nguyen and Choi (2009) optimized the design of an MR damper for a vehicle suspension system by finite element analysis. The damping force, dynamic range, and valve dimensions were considered as design optimization parameters. In that research a linear mono-tube MR damper was used for a vehicle suspension system as shown in Fig. 7. In this damper design, the piston has divided the damper into two parts: an upper chamber and a lower chamber. The authors analyzed the performance of the optimized design for various values of the excitation current, and the maximum yield stress force exhibited by the optimal model verified the design configuration. Mangal and Kumar (2015) developed an optimal MR damper model by considering various geometric parameters. They used the Taguchi coupled finite element method with the help of ANSYS simulation software.

In the design optimization, the damper cylinder thickness, the pole length, the circular distance from piston rod to coil width, and the clearance between piston and cylinder were varied and a total of 18 different models were developed. In ANSYS the damping force for each model was calculated and the optimal force was detected as the optimal force for providing the maximum damping force. Mangal and Kumar (2015) validated their simulation model by developing an experimental model, where the simulation and experimental results for an optimal model were very close to each other as shown in Fig. 8. The maximum percentage error between the model and experimental results for the optimal MR damper varying current was 5.42%, which was found at a current of 0.1 A.

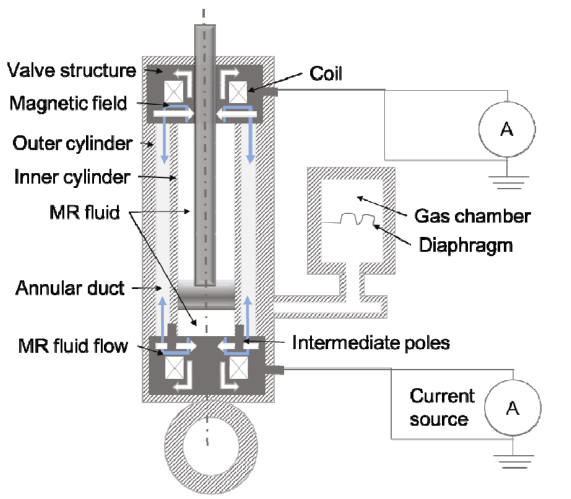


Fig. 7 Optimal MR damper design for vehicle suspension system

Gavin *et al.* (2001) optimized the design of an MR damper with respect to minimum power consumption and minimal induction time constant, as presented in Fig. 9. For the optimal design the authors considered a variety of parameter conditions such as force capacity, electrical characteristics, and the size of the device.

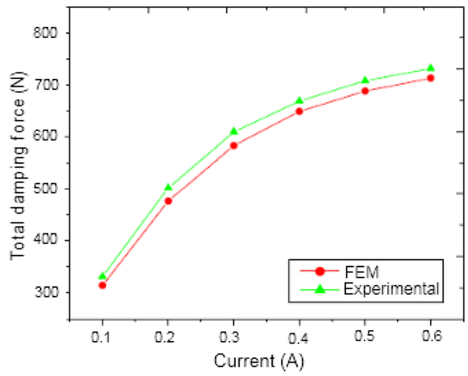


Fig. 8 Comparison of an optimal MR damper model simulation (FEM) and experimental results. Reprinted from (Mangal and Kumar, 2015), Copyright 2015, with permission from Springer

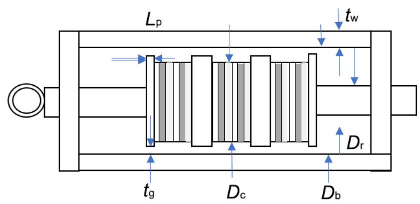


Fig. 9 Optimal design of a typical MR damper

L_p: piston pole length; t_w: cylinder wall thickness; t_g: thickness of gap between wall and piston poles; D_c: diameter of steel core; D_b: casing diameter; D_r: diameter of piston rod

From the optimal damper experimental model, the maximum delivered force is 4 kN, which is generated when the damper is excited with an electric current of 10 A. It shows that an MR damper can produce a large force with a low current supply.

Moreover, it takes only few milliseconds from the off state to the on state of the MR damper to generate that force.

Ferdaus *et al.* (2014b) proposed an optimal design for a mono-tube linear MR damper by considering various damper configurations. They considered various piston profiles, a variable piston diameter, MRF gap, and three different numbers of coil stages. The planning of the model configuration for examining the optimal model is presented by the flow diagram as Fig. 10 (Rashid *et al.*, 2015). By considering these parameters Ferdaus *et al.* (2014b) have developed a total of 45 models in ANSYS platform and have calculated the damping forces for them. Among them the optimal MR damper, which is configured with a single stage coil and top and bottom chamfered piston ends, provides the maximum force

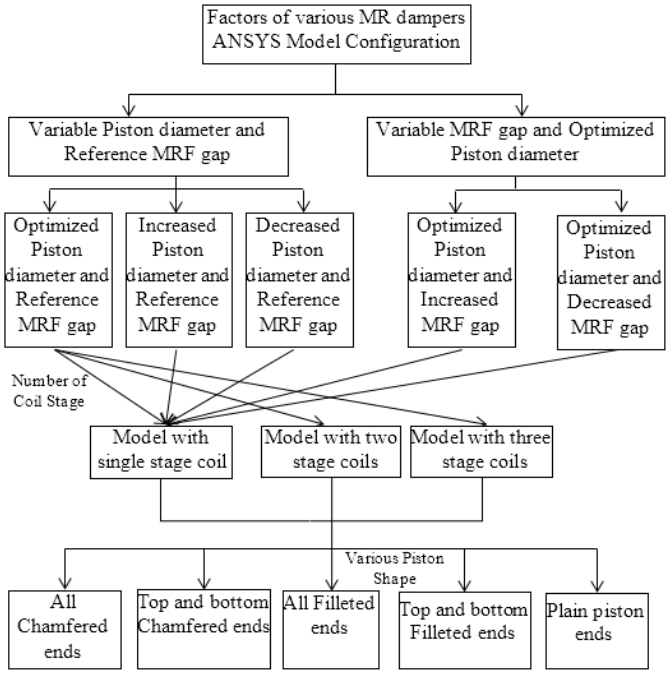


Fig. 10 MR damper design optimization factors flow diagram. Reprinted from (Rashid *et al.*, 2015), Copyright 2015, with permission from Springer

as compared with the other configurations by maintaining the same input current and piston velocity. The authors have performed experimental analyses and compared them with the optimal model results, and they are very close to each other with a maximum error of 1.45%. Thus, improvements of MR damper design have been made in several designs where an increased MR damper force was achieved with very low currents. However, there is still scope for research to further improve MR damper force optimization. In the next few sub-sections, the design and applications of different types of MR brake are highlighted.

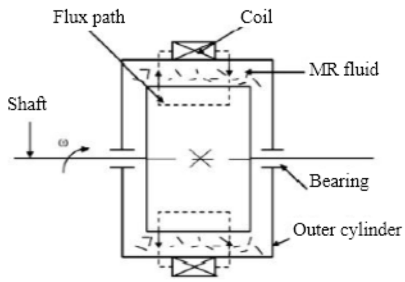


Fig. 11 Elementary idea of drum type MR brake. Reprinted from (Huang *et al.*, 2002), Copyright 2002, with permission from Elsevier

3.1 Design advances in drum type MR brakes

Research has been done focusing on the radial gap as a way to enlarge the shear mode's effective area in a drum type MR brake (Huang *et al.*, 2002; Senkal and Gurocak, 2009; Kikuchi and Kobayashi, 2011). Huang *et al.* (2002) discovered that by making the cylinder thicker, the shear mode's working area around the radial gap can be enlarged as shown in Fig. 11. Another paper has proposed an optimized flux path in order to improve the performance of the MR brake, where a serpentine flux path has been developed, as shown in Fig. 12 (Senkal and Gurocak, 2009).

3.2 Performance enhancement in disc type MR brakes

Like the drum type MR brake, it is possible to enhance the disc type MR brake's performance by enlargement of the working area of the shear mode. The location of the effective area of a disc type MR brake is not the same as that of a drum type MR brake.

Here the effective area is situated around the end face gap in the axial direction. In the early stages of development of disc type MR brakes, Li and Du (2003) published the basic design concept of a disc type MR brake with a single disc, as shown in Fig. 13. Park *et al.* (2006) designed a disc type MR brake to

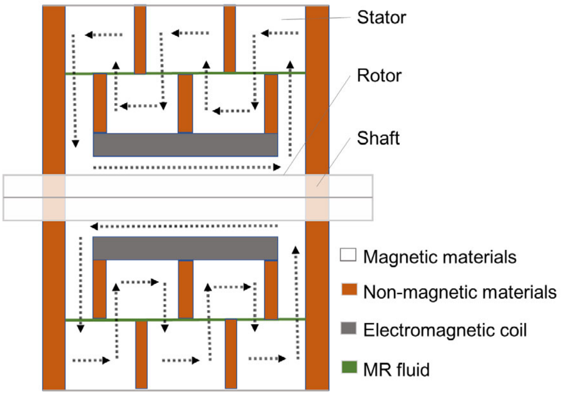
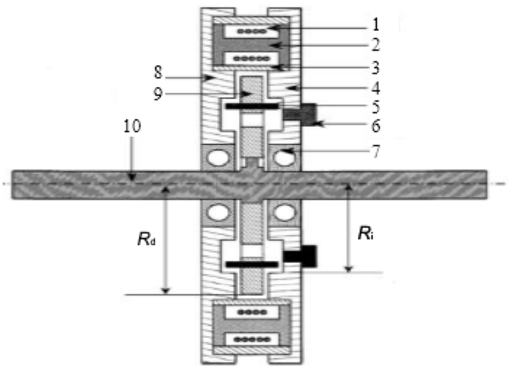


Fig. 12 Serpentine flux path in a drum type MR brake



No.	Part description	No.	Part description
1	Wire	6	Filling plug
2	Bobbin shaft (core)	7	Ball bearing
3	Enclosure	8	Housing (left)
4	Housing (right)	9	Rotor
5	Mixing pin	10	Shaft

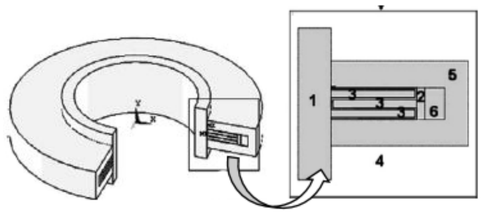
Fig. 13 Cross-sectional view of the disc-type MR brake. Reprinted from (Li and Du, 2003), Copyright 2003, with permission from Springer

R_d and R_i are the distances from the shaft to the end of the rotor and end housing, respectively

make it appropriate for automobile applications with the help of a sliding mode controller as shown in Fig. 14. The multi-disc design concept is a design optimization of the disc type MR brake to maximize brake torque for a specific weight.

3.3 Advances in hybrid type MR brakes

Besides the single and double coil hybrid type MR brake configurations, there exists another radical approach to the hybrid type MR brake. It is shaped like a T and this T-shaped assembly is presented in Fig. 15. The T-shaped configuration was introduced in the research of York *et al*. (1997) and was analyzed later by several researchers (Avraam *et al*., 2010; Hung and Bok, 2012; Nguyen and Choi, 2012a; 2012b). Like the other hybrids, the T-shaped hybrid type MR brakes also have rotor and stator coil configurations as displayed in Figs. 15a and 15b.



No.	Part description	No.	Part description
1	Shaft	4	Housing (right)
2	Ring holding stator	5	Mixing pin
3	Disks (top and bottom) and stator (center)	6	Fill plug

Fig. 14 Two-disc MR brake. Reprinted from (Park *et al*., 2006), Copyright 2006, with permission from Elsevier

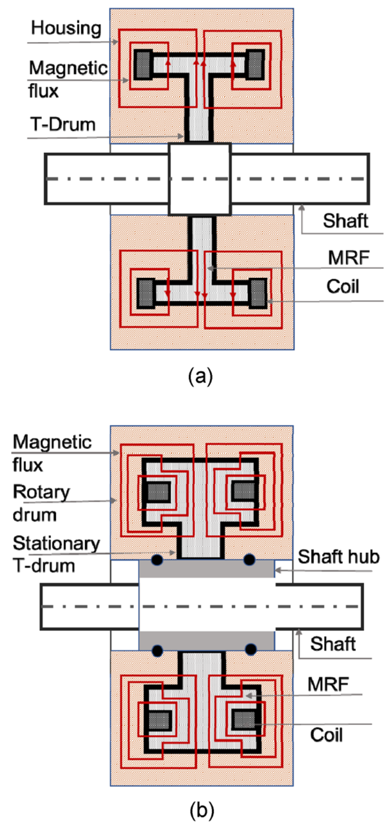


Fig. 15 T-shaped hybrid type MR brake with stator coil (a) and rotor coil (b)

In this section three types of MR brake were presented to highlight their advances in design and performance in seeking the optimal MR brake. This study will guide readers in more research to enhance the performance of MR brakes.

4 Design and modeling of energy-saving and self-powered MR dampers

Normally electromagnets such as coils or solenoids are the source of the applied magnetic field in an MR damper. Continuous operation of this coil would consume much energy and produce heat causing an increase in temperature of the MR fluids as well as in the body of the dampers. The viscosity and volume of a fluid are closely related to the temperature, and here, in the MR fluids, the viscosity decreases with rising temperature. As the damping force of an MR damper is directly related to the viscosity of the MR fluid, the performance of damper gets affected, so that post-yield damping decreases. The gas of the accumulator is also heated, which causes a further increase in the stiffness of the damper. Several papers described research on controlling the MR damper. However, only a limited amount of analytical and experimental studies have been carried out on the thermal effects on the performance of the MR dampers. Researchers have done many analyses (Böse and Ehrlich, 2012; Ferdaus *et al*., 2014c) on reducing energy consumption and heat generation in MR dampers. The concept of a hybrid magnetic circuit is a new one in which the hybrid circuits are a combination of a permanent magnet (AlNiCo) and an additional coil. In another approach a permanent combination of hard magnetic NdFeB or $SmCo_2$ and low coercive AlNiCo was used, beside this, an electromagnet coil or solenoid was used. Hard permanent magnets create a base magnetic field strength in the MR gap of the damper and the corresponding damping force. In cases of the combination of the AlNiCo magnet and coil, magnetization is controlled by the current in those coils, so the base magnetic field strength may be increased or decreased, depending upon two factors: the polarity of the AlNiCo magnetization and the amount of current passing through the coils.

Vibration and shock create mechanical energy which can be used as a power source, and a large amount of this mechanical energy is lost during the daily usage of an automobile under road irregularities and similar real-life activities. It is clearly seen that the wasted energy by vibration depends upon highway roughness, car speed, and the rigidity of the suspension and its damping coefficient (Velinsky and White, 1980), and it has been reported that the total energy dissipation of the four dampers of a vehicle reached 200 W when travelling on a rough highway at a speed around 13.4 m/s (Segel and Lu, 1982; Fodor and Redfield, 1993). An external power supply would not be needed if this waste energy could be transformed into electrical energy (Scruggs and Iwan, 2003; Lesieutre *et al*., 2004), and no extra sensor would be required to measure the dynamic responses. This indicates the achievability of self-sensing and self-powered MR damper technology. That technology would be able to improve the credibility of whole MR damper systems. The massive advantages of it include weight and size reduction, a simpler way of conservation, and little maintenance cost. These features are very beneficial under some extreme conditions such as earthquakes when the external power supply may get cut off. Recent advances in self-powered and self-sensing MR dampers with smart features are presented in the next sub-sections.

4.1 MR damper system with energy-saving magnetizing circuit

Sato and Umebara (2012) developed an energy-saving technique to magnetize the MRF of MR dampers. They replaced the conventional electromagnet, i.e., coils, with a combination of permanent magnet material rods and coils as shown in Fig. 16. In extended operation, the electromagnet of a conventional damper consumes a large amount of power. However, the model they developed consumes near zero electric power in applying external excitation to the fluid of the MR damper. The device is capable of maintaining the necessary field intensity continuously with a very small power consumption.

To evaluate the performance of their proposed hybrid magnetic circuit, Sato and Umebara (2012) developed a test apparatus as shown in Fig. 17, which contains an air compressor, double rod cylinder, and a container of MRF. The cylinder has two chambers, air pressure is provided to one of them, and the other is filled with MR fluid. The pressurised air pushes the piston, and consequently the MRF goes out from the other chamber of the cylinder and flows through the hybrid magnetic circuit. The flow rates (Q) of the MR fluid passing through that device are estimated from the velocity of the piston rod. The test has established the efficiency of their hybrid magnetic circuit in saving electric power and in supplying a magnetic field to the fluid. Their design is appropriate for MR fluid applications where a constant viscosity for a period of longer than 0.7 s is to be maintained.

4.2 Smart passive system-based MR damper

Cho *et al*. (2005) and Choi *et al*. (2007) introduced an MR damper with power generation ability that consists of an EMI device for reducing suspension vibrations. The proposed model comprises an MR damper and an EMI system containing a permanent magnet and a coil. It gives a mechanism for self-powered vibration control and the EMI exploits vibration energy to produce electrical energy. It is, however, large, and that may impact negatively on its application in restricted spaces such as in cars, buses, motorcycles, and robots.

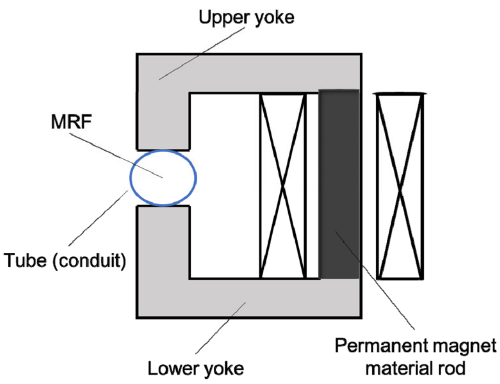


Fig. 16 Hybrid magnetic circuit of MR damper to control viscosity of MRF

4.3 Self-powered and sensing control system based on an MR damper

Wang *et al*. (2009) presented a new self-powered MR damper with a sensing semi-active control system. The system consists of a rack and pinion mechanism, a linear permanent magnet DC generator, a current controlled MR damper, and a control circuit. Fig. 18 displays the flowchart of the proposed model. The model was tested for five control strategies: ideal active control, two semi-active controls, and two self-powered semi-active controls. In all five cases the results showed similar control performance in respect both to pier response and to bearing response and only one accelerometer to monitor the response is needed. The shortcoming of this model is the complicated arrangement of four parts and the consequently increased weight.

4.4 MR damper-based self-powered smart damping system

Jung *et al*. (2008) designed, manufactured, and tested a self-powered smart damping system using an MR damper for a real-scale structure. The system was designed specially with a large-scale MR damper and big scale EMI part as shown in Fig. 19. The experiment result demonstrated the ability of this system to produce enough induced current for the damper. The size of the individual parts is large and only suitable for civil structures. Such a large-scale MR damper is usually implemented in civil structures such as

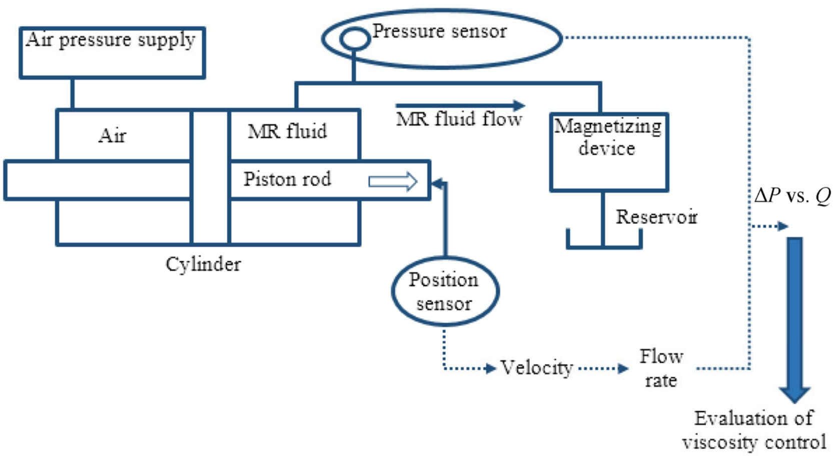


Fig. 17 Performance evaluation of magnetizing device for MR damper (Sato and Umebara, 2012)
ΔP is the constant pressure drop

buildings, bridges, etc. Some of these implementations are described in (Cha *et al*., 2013a; 2014; Friedman *et al*., 2015; Cha and Agrawal, 2016). These studies show improved vibration reduction in the structures.

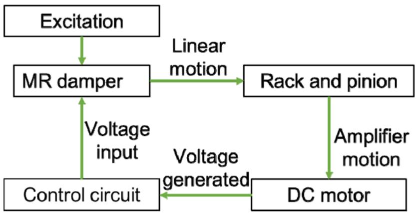


Fig. 18 Flow diagram of an energy-harvesting MR damper-based control system

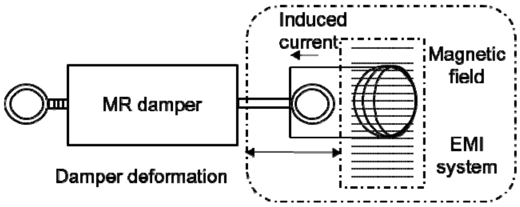


Fig. 19 Schematic of self-powered smart damping system employing MR damper and EMI

4.5 Self-powered MR damper as an energy-harvesting dynamic vibration absorber

Choi and Wereley (2009) developed a self-powered MR damper attached to an energy-harvesting device containing a stator, a permanent magnet, and a spring, which operates as an energy-harvesting dynamic vibration absorber (DVA) as shown in Fig. 20. The controlling technique of the model is stable and may not be appropriate for all applications, but the model has shown good vibration isolation performance of a self-powered MR damper without the need for a sensor and control algorithm.

4.6 Self-powered MR damper-based vibration reduction system

Sapiński (2010) introduced a power generator for a linear MR damper known as an electromagnetic power generator. In this model the electromagnetic generator has a mechanical and electrical sub-system and the full system contains these sub-systems and an MR damper as shown in Fig. 21. The generated force of this model is expressed by

$$F=(c_1|i|+c_2)\tanh\left\{\beta\left[\left(\frac{\mathrm{d}z}{\mathrm{d}x}-\frac{\mathrm{d}x}{\mathrm{d}t}\right)+p_1(z-x)\right]\right\} +(c_3|i|+c_4)\left[\left(\frac{\mathrm{d}z}{\mathrm{d}x}-\frac{\mathrm{d}x}{\mathrm{d}t}\right)+p_2(z-x)\right], \quad (1)$$

where c_1, c_2, c_3, and c_4 are constants in the MR damper model, and β, p_1, and p_2 are scaling parameters enabling transition, in the pre-yield region, from negative to positive velocities.

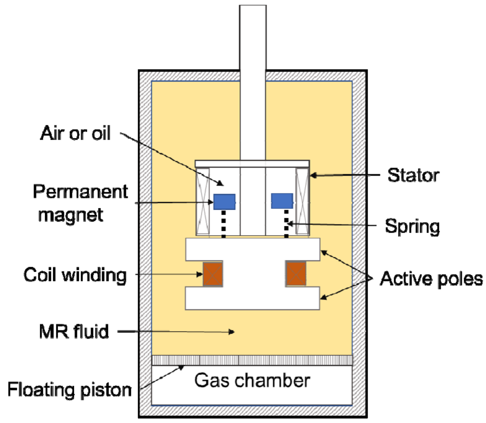


Fig. 20 Configuration of a typical self-powered MR damper

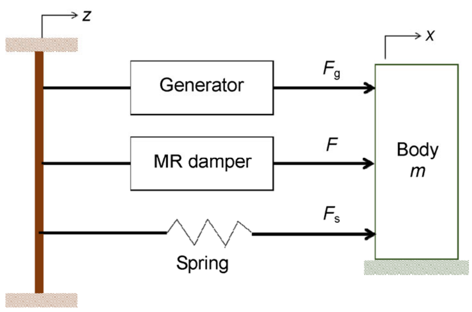


Fig. 21 Schematic diagram of a self-powered MR damper-based vibration reduction system

F_g: generator force; F: damping force; F_s: force generated from spring; x: final displacement; z: initial displacement

The generator works as an MR damper energy source and the necessary energy is absorbed from the environmental vibrations. Energy achieved by the generator accounts for almost 2.5% of energy generated by the MR damper in its mechanical sub-system. This research mainly focused on the performance and design construction of the generator.

4.7 Self-powered MR damper with self-sensing ability

Chen and Liao (2012) designed, fabricated, and tested a self-powered and self-sensing MR damper that integrates energy-harvesting and dynamic sensing damping technology into a single device. Fig. 22 shows the block diagram of the experimental setup.

The experimental results from this MR damper model demonstrated its capability of generating power and its velocity-sensing abilities and relevance to different dynamic methods. This is actually a large double-ended MR damper and is thus more suitable for civil structures.

4.8 Linear MR damper with energy-harvesting capability

Sapiński (2014) designed and tested an energy-harvesting linear MR (EHLMR) damper prototype which is a combination of three main components in one device. These parts include a damper piston assembly, a power generator for producing electrical power, and a conditioning electronics unit.

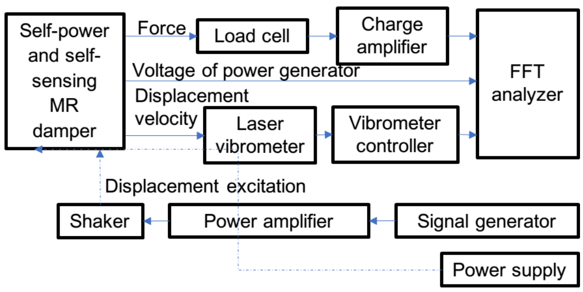


Fig. 22 Block diagram of a self-powered and self-sensing MR damper system (FFT is fast Fourier transform)

In this model, due to its self-powered and self-sensing capability there is no need of an external power supply or displacement sensors. However, the output voltage of the self-powered MR damper model is limited. Table 2 summarizes the main features of the self-powered MR dampers described.

In this section, different designs of self-powered and self-sensing MR damper were presented. The purpose of these designs is to generate energy for current supply to drive the MR damper. Generally, the current in the MR damper is supplied externally, but this energy can be saved if an optimal self-powered MR damper is implemented. The limitations of these designs are highlighted to indicate where more research is needed to discover more effective, lower cost, and simpler designs.

5 Conclusions

The MR damper is a smart semi-active device, which has some advantages over passive and active devices such as controllability of current supply to the damper, comparatively light weight, and low power consumption. The damper contains a smart fluid called MR fluid and works on different fluid flow

Table 2 Summary of various self-powered MR dampers

Reference	Focus	Method	Remark
(Cho *et al.*, 2005)	Power generation	EMI device	Large, not applicable in confined spaces
(Jung *et al.*, 2008)	Self-powered	Big scale EMI	Only for civil structures
(Wang *et al.*, 2009)	Self-powered with sensing	Rack and pinion mechanism	Arrangement of four parts is very complicated and increases the weight
(Choi and Wereley, 2009)	Self-powered	Energy-harvesting device such as a stator, a permanent magnet, and a spring	Control algorithm is not appropriate for variety of applications.
(Snamina and Sapiński, 2011)	Vibration reduction	Mechanical and electrical subsystem of the electromagnetic generator	Needs a large space
(Chen and Liao, 2012)	Self-powered and self-sensing	Energy harvesting, dynamic sensing damping	Only modeled for double-ended MR dampers and suitable for civil structures
(Sapiński, 2014)	Energy harvesting, dynamic sensor	Electromagnetic energy extractor	Limited range of output voltage

modes. The basic design and construction of MR dampers, along with the configurations of their various types, are discussed in this paper to understand their versatile applicability for a range of environments and purposes. The techniques for characterizing the non-linear complex behavior of MR dampers are demonstrated using some well-known damper mathematical modeling methods and all these are summarized here. To cope with different applications, design modification, optimization, and advancement are covered in this review. Saving energy is the ultimate demand at present and is a challenge to modern technology. In that connection, self-sensing and power saving, i.e., the energy-harvesting capability of an MR damper from the wasted mechanical energy, are compared here with their proper modeling. In future, a new type of self-powered and self-sensing mono-tube MR damper could be built, which is constructive to combine power generation and sensing ability within one small device, like the mono-tube MR damper, and suitable for small-scale applications, such as vehicle suspension systems. That damper would combine the advantages of energy harvesting (reusing wasted energy) and MR damping (controllable damping force). This multifunctional integration would bring great benefits such as energy saving, size and weight reduction, lower cost, higher reliability, and less maintenance for MR damper systems. By comparison with conventional mono-tube MR dampers, this proposed energy-generated MR damper design would have an extra permanent magnet, nonmagnetic material, and an external coil which would work as a power generator in the proposed model. Overall, the optimal design, fabrication and smart application of various MR dampers, and the latest advances in self-powered and self-sensing technology are reviewed in this paper. This work may be useful to implement MR dampers in various structures for vibration control with minimum current supply.

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中文概要

题　目：磁流变阻尼器最新进展综述：优化设计和应用

概　要：本文对各种磁流变阻尼器的优化设计、制造和智能应用以及自供电和自感应技术的最新进展进行了综述。本文讨论了磁流变阻尼器的基本设计和结构以及各种类型的配置，以了解它们在各种环境和目的下的多功能性。为了应对不同的应用，本文介绍了设计的修改、优化和改进。节能是当前的终极需求，是对现代技术的挑战。磁流变阻尼器需要改进，以确保较低的电流供应得到较高的效力。这项工作将有助于在各种结构中使用磁流变阻尼器，使其以最小的电流供应进行振动控制，并在优化中获得最佳结果。

关键词：磁流变阻尼器；自供电；振动控制；节能；优化和提升