Korea-Australia Rheology Journal, 28(4), 355-379 (November 2016) www.springer.com/13367
DOI: 10.1007/s13367-016-0035-2

Review

Advancement in energy harvesting magneto-rheological fluid damper: A review

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(Received May 22, 2016; final revision received August 18, 2016; accepted September 6, 2016)

In this paper, a comprehensive review of the present literature on energy generated magnetorheological (MR) fluid based damper, modeling and applications of the MR damper are presented. The review starts with an introduction of the basic of MR fluid and their different modes, consequences with different types of MR fluids based devices, and their relevant applications. Besides, various forms of MR damper and its applications are presented. Following this, the modeling of the MR fluids and the modeling of the MR fluid based damper are deliberated according to arrangement and configurations. Finally, the review ends with the design and advancement issues, performance analysis matters, and analytical modeling of energy generated magnetorheological fluid damper systems.

Keywords: energy generation, MR damper, MR fluid, models, design

1. Introduction

At present, magneto-rheological fluid based dampers are promising for vehicle suspension system. With an applied magnetic field, MR fluid can change into the semi-solid state from the liquid state within a few milliseconds (Chen and Liao, 2010; Kordonsky, 1993a). By using this principle, the MR damper can create controllable damping force. Generally, the combination of high-performance MR fluid application systems needs several factors such as materials properties, viscosity, temperature etc. (Choi *et al.*, 2016). Sensors are very useful for measuring the dynamic response as well as to ensure full use of the controllable damping characteristics (Kaluvan *et al.*, 2016). It includes correlative dislocation or velocity with MR damper diagonally and its installation and maintenance system could be complex. Moreover, there are various types of developed models for the characteristics of MR dampers. With regards to the method of modelling, the models are classified as parametric (Şahin *et al.*, 2010; Wang and Liao, 2011) and non-parametric dynamic models (Choi *et al.*, 2001; Ehrgott and Masri, 1992; Jin *et al.*, 2005; Kim *et al.*, 2008; Song *et al.*, 2005; Song *et al.*, 2007). By considering the characteristics shown by the established models, they can be further classified as quasistatic models (Chooi and Oyadiji, 2008; Hong *et al.*, 2008) and dynamic models. Considering the reversibility of the established models, they are classified as dynamic models (Wang and Liao, 2005; 2011) and inverse dynamic models (Tsang *et al.*, 2006).

Furthermore, MR damper vibration and shock create mechanical energy which is possible to use as a power source, since a huge amount of this mechanical energy is lost during daily usage of an automobile in irregular surface of roads. It is concluded that the wasted energy by vibration is caused by highway roughness, car speed, suspension rigid, and damping coefficient and it has reported that the total energy dissipation of four dampers of traveler vehicle reached 200 W when going on a haggard highway at more or less 13.4 ms^{-1} (Fodor and Redfield, 1993; Segel and Lu, 1982; Velinsky and White, 1980). There would be no need of external power supply by transforming this wasted energy into electrical energy (Lesieutre *et al.*, 2004; Scruggs and Iwan, 2003). Further there will be no requirement for extra sensors when dynamic responses are possible to measure, with the exception of an addition sensor. This self-sensing and self-powered device is an energy saving technology with no environmental effects. In addition, the reliability of the total MR damper system will be improved with the help of this technology. The weight and size would definitely be reduced, which is a huge benefit of this system with its design simplicity and low conservation budget. In some life threatening situation like earthquakes this self-powered MR damper technology would works perfectly since there are chances of cutting off the power supply.

This concept of self-sensing and self-powered damper has been used to develop energy-saving smart MR damper. Many researchers are trying to develop and improve the self-powered technology. Nakano *et al.* (2003) observed that producing current in the reproduction process is better to fulfill the power demand in the dampers. Hsu (1996) has measured the total regenerative power, which has reached 100 W when going on the road at 16 ms^{-1}. Moreover, Dong (2015) measured in D grade road the generated energy is about 45 W when velocity is around 0.6693

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ms^{-1}. Energy dissipation in vehicle's passive and active suspension system is analyzed by Yu *et al.* (2005). Concerning with the former research on self-sensing controllable dampers, an integrated magneto astrictive position sensor was developed for MR dampers by Russell (2001). It was difficult to develop commercially due to its complicated structure, proper manufacturing action and costly magneto astrictive materials. Nehl *et al.* (1996) proposed an integrated self-energizing comparative velocity sensor which is impossible to center within MR dampers. The sensor's coil is wounded on MR damper's dust tube resulting performance degradation of the sensor and limit their usage in MR dampers. Wang *et al.* introduced an electromagnetic induction based MR damper and compact with a similar displacement sensor too (Wang and Bai, 2011; Wang and Wang, 2009; Wang *et al.*, 2010). This sensing process consists of complicated circuits for signal processing. Or *et al.* (2008) presented an MRD including piezoelectric based force sensor. Some research have been done previously on MR damper's capability to generate power. Cho *et al.* (2005) presented an energy harvested MR damper that consists of an electromagnetic induction (EMI) device in order to mitigate vibrations from suspension. It gives a technological strategy for vibration control with power generation ability, where the EMI converts the vibration energy into electrical energy. Choi and Werely (2009) have asserted some corresponding researches. They studied the obligation and usefulness of self-powered MR damper and used a spring-mass electromagnetic induction device. The generated power is supplied to MR damper, which eliminates the necessity of using additional sensors in their former two works. In addition, Sapiński (2010) demonstrated a linear MR damper's power generator called electromagnetic power generator. Mainly the performance and construction of the generator were focused in their research. Ahamed *et al.* (2016) proposed a design of energy generated MR damper for vehicle suspension system. The magnet and coil arrangement are used for generation of energy from vehicle vibration. In the former research on self-powered MR dampers with sensing ability have revealed various expectant results, however a few research has been accomplished on MR damper that combines the self-powered and self-sensing ability into one device. Chen and Liao (2012a) have proposed a MR damper with self-powered and self-sensing capability. Their design is developed for double ended MR damper and applicable to civil structures. Ferdaus *et al.* (2013) proposed a self-powered MR damper model which has self-sensing ability. Permanent magnet, coil, and spring arrangement are in this proposed model to generate energy.

With the purpose to identify the achievement of research and improvement of self-powered MR damper, an inclusive review is required. This paper offers the survey of current improvement and advancement of self-powered MR regarding different improvements of structural and designs besides modeling techniques considered in each improvement.

2. Magneto-rheological (MR) Fluid

A magneto-rheological fluid is a type of smart fluid which is prepared by mixing of fine particles with low viscosity. In the presences of an external magnetic or electric field MR fluids offer a quick, reversible and harmonic transformation to semi-solid state from free-flowing state in a few milliseconds and can be formed chain-like fibrous structure (Chen and Liao, 2010; Kordonsky, 1993a; 1993b; Peng *et al.*, 2014). It has some striking benefits such as a much lower sedimentation rate than conventional fluids, large operational temperature range, and usefulness in existing controllable high damping force. Moreover, it glances an improvement in apparent yield stress (Ngatu *et al.*, 2008), quick response, and low power consumption (Kamath *et al.*, 1997). In MR fluid the micron size (20-50 microns) magnetic material is normally suspended in oil like carrier fluid. The maximum force delivered by MRD is determined by the MRF properties, flow design, and MRD's size. Table 1 presents the properties of the MRF.

2.1. Different operational modes of MR fluid

Practically MR fluids function at three altered modes such as shear, squeeze, and valve mode. These three modes have three different flow rules. On the other hand, Goncalves and Carlson (2009) recently proposed a new working mode known as magnetic gradient pinch mode. By combining these modes MR devices also can work. Another name of the valve mode is flow mode. When MR damper operates in valve mode, the MR fluid itself impedes the MR fluid flow from one reservoir to another and it is the most commonly used mode of MR damper among the three modes as is displayed in Fig. 1a (Spencer Jr *et al.*, 1998). In addition, while a thin layer of MRF ranging from around 0.005 inches to 0.015 inches is inserted in the middle of two paramagnetic moving surfaces, the MRF devices can be worked in shear mode which is displayed in Fig. 1b (Goncalves and Carlson, 2009). Shear mode is

Table 1. MR fluid (MRF) properties.

Representative feature	MR fluids
Range of yield stress	50-100 kPa
Supplied voltage and current	2- 24 V @ 1-2A
Response time	Few millisecond
Operational field	250 kA/m
Energy density	0.1 J/cm^3
Stability	Good for most impurities
Operational temperature	From –40°C to +150°C

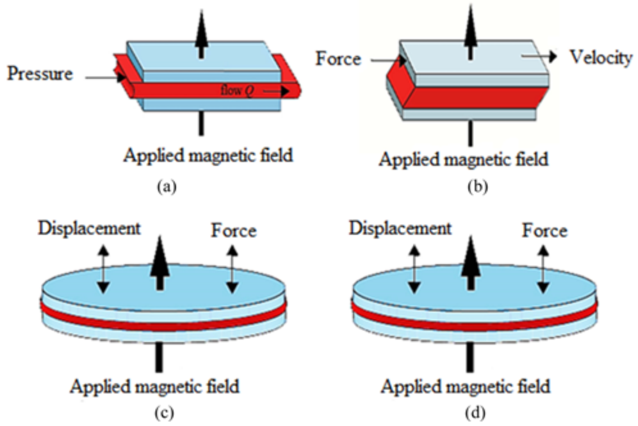


Fig. 1. (Color online) (a) Valve mode (Yang *et al.*, 2002), (b) direct shear mode (Zhu *et al.*, 2012), (c) squeeze mode (Guglielmino *et al.*, 2008), and (d) magnetic gradient mode (Goncalves and Carlson, 2009).

primarily suitable for dampers those can provide small forces or in compact clutches and brakes. When an MRF thin film of a width of 0.02 inch is inserted between pole surface, the MRF devices can operate by using squeeze mode presented in Fig. 1c (Guglielmino *et al.*, 2008).

Moreover, the main idea of magnetic gradient pinch mode is like the flow mode, however, it has numerous arrangement of the magnetic circuit. Figure 1d shows the magnetic gradient pinch mode with magnetic poles, which are organized axially along with flow direction and divided by nonmagnetic substantial. This types of poles organization of the magnetic gradient pinch mode can produce elliptical magnetic fibrils that would resist the passing of MRF in valve gap. Among all attributes, the special attribute of this mode is the gradient would knowingly be increased proportionally with the applied magnetic field in the middle of pressure-velocity affiliation (Goncalves and Carlson, 2009). It is exceptional, under any magnetic field asset alterations the gradient tends to keep on constant since in the ordinary flow mode. Another benefit is the probability of utilizing MRF with rougher particles of ranges like 100 μm, since a bigger orifice is achievable to be utilized with this mode (Goncalves and Carlson, 2009).

2.2. Various models for MR fluids

For improvement of the MRF devices, MR fluids model is an important part. All MR fluid models have shown in Table 2. At first, in 1969 Bingham introduced flow equation which is known as Bingham flow equations (Goncalves *et al.*, 2006). After this work, modeling of MR fluids acknowledged significant consideration.

Furthermore, the present models are very accurate. To characterize the MR fluids different nonlinear models have been used such as Bingham plastic model (Carlson and Jolly, 2000; Kato and Phillips, 1969) the Biviscous model (Stanway *et al.*, 1996) and the Herschel-Bulkley model (Choi *et al.*, 2005; Wang and Gordaninejad, 1999). MR fluid's Bingham model contains a moveable and accurately rigid plastic material that is associated with the corresponding Newtonian material. The equations of this model have been exposed in Table 2. Figure 2 shows the Bingham plastic model to portray the yield stress's performance field-dependency. Moreover, to operate the MR devices in squeeze flow mode, the shear stress equation of the Bingham plastic model is widespread interested in the

Table 2. MR fluid models.

Model name	Equation	Symbols	References
Bingham Plastic Model	$\tau = \tau_y(H)\mathrm{sgn}(\dot{\gamma}) + \eta\dot{\gamma}$, $\tau > \tau_y$ $\tau = G\dot{\gamma}$, $\tau < \tau_y$	H = magnitude of applied field $\dot{\gamma}$ = fluid shear strain rate $\mathrm{sgn}(\cdot)$ = signum function η = plastic viscosity (at zero field) τ = shear stress τ_y = yield shear stress G = complex modulus of the material	(Jolly *et al.*, 1998; Wang and Liao, 2011; Weiss and Duclos, 1994)
Biviscous Model	$\tau = \begin{cases} \tau_y(H) + \eta\dot{\gamma}, & \lvert\tau\rvert > \tau_1 \\ \eta_r\dot{\gamma} & \lvert\tau\rvert < \tau_2 \end{cases}$ $\tau_y(H) = \tau_1\left(1 - \frac{\eta}{\eta_r}\right)$	η_r and η = the elastic and viscous fluid properties	(Stanway *et al.*, 1996; Wang and Liao, 2011; Wilson and Thomas, 2006)
Herschel-Bulkley Model	$\tau = \left(\tau_y(H) + K\lvert\dot{\gamma}\rvert^{\frac{1}{m}}\right)\mathrm{sgn}(\dot{\gamma})$	K and m = the fluid parameters	(Choi *et al.*, 2005; Wang and Liao, 2011; Wang and Gordaninejad, 2007)

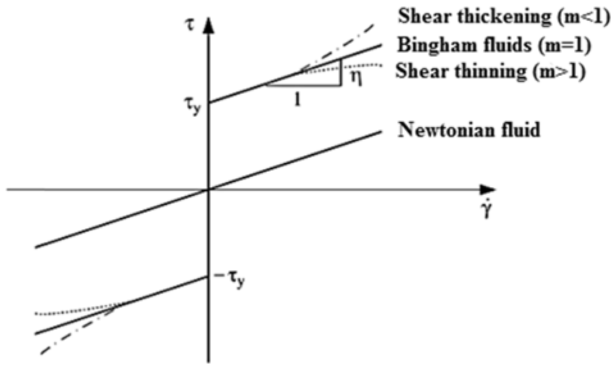


Fig. 2. Bingham model and Herschel-Bulkley model (Koo *et al.*, 2006).

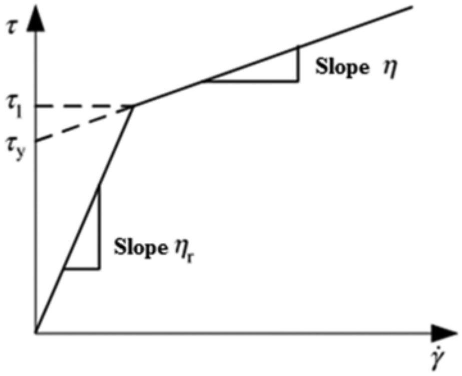


Fig. 3. Idealized biviscous constitutive relationship (Stanway *et al.*, 1996; Wang and Liao, 2011).

biviscous relationship as shown in Table 2. Figure 3 displays the Biviscous model.

Conversely, the model presented in Fig. 2 is a substitute for the Bingham plastic model. The post-yield and shear thinning behavior of the MRF is explained usually by this model. The equation of this model is shown in Table 2.

2.3. MR devices

As MR fluids' properties are controllable by applied magnetics field's strength, they are suitable for the requirement of variable force applications. The commercialization of MR technology started in 1995. During the past decade's commercially available products (or near commercialization) have been developed rapidly for example MR fluids used. Different MR devices and their application are displayed in Table 3.

3. MR Damper and Its Application

MR damper works as a vibration isolator, which is loaded with MRF and controlled by an electromagnetic field. It follows the semi-active control strategies. At present, manufacturers are exposing more attention to the MR dampers. The development of MR fluids by Lord Corporation is an example and they are currently manufacturing MR truck seat dampers (Poynor, 2001), which are possibly one of the most effective marketable MR dampers to date. The applications of MR damper are shown in Table 4.

Table 3. MR damper devices and applications.

MR devices	Figure No.	Application	References
MR damper	4	Heavy truck, knee prosthetics of limbs, humanoid robot, haptic devices, motion master	(Carlson and Chrzan, 1994; Yao *et al.*, 2002)
Brakes and clutches	5, 6, 7, 8	Aerospace, Industry, haptic device, aerobic exercise machine	(Benetti and Dragoni, 2006; Lee *et al.*, 1999; Nguyen *et al.*, 2016)
Polishing devices	9	Ocular glasses, ceramics, plastics, and few nonmagnetic materials	(Wang *et al.*, 2013)
Hydraulic valves	10	Actuator, converters	(Kordonsky, 1993b; Kordonsky *et al.*, 1995)
Seals	11	Rotary shaft	(Kordonski and Gorodkin, 1996)
Composite structures	12, 13	Plates, panels, beams and bars, or constructions	(Weiss *et al.*, 1996)
Pneumatic actuator motion control systems	14, 15, 16	Set in parallel along with a linear resistance component	(Wang and Meng, 2001)
Flexible fixtures	17, 18	Turbine blades	(Tang *et al.*, 1999)
MR valves	19	Actuator	(Guo *et al.*, 2003)
MR device based MR elastomers	20, 21	MRE force sensors, automotive bushings and engine mounts	(Sun *et al.*, 2016)

Table 4. Application of MR dampers.

Application	References
Automobile	(Du *et al.*, 2005; Dutta and Choi, 2016; Dutta *et al.*, 2016; Lee *et al.*, 2006a; Yang *et al.*, 2016; Yao *et al.*, 2002)
Railway vehicle	(Ha *et al.*, 2008; Lau and Liao, 2005; Liao and Wang, 2003; Oh *et al.*, 2016; Wang and Liao, 2009)
Civil structural applications	(Jung *et al.*, 2004; Kciuk and Turczyn, 2006; Lee *et al.*, 2006b; Medina, 2016; Ritchey, 2003; Symans and Constantinou, 1999; Yang *et al.*, 2004)
Mechanical structure	(Sapiński, 2009; Wang and Meng, 2001)
Social application	(Case *et al.*, 2011; 2013; Herr *et al.*, 2006; Kim and Oh, 2001; Klingenberg, 2001)
Helicopter leg	(Marathe *et al.*, 1998)
Household application	(Chrzan and Carlson, 2001; Spelta *et al.*, 2009)
Military equipment	(Ha *et al.*, 2013; Sedlák and Kuffová, 2015)

Fig. 4. (Color online) MR damper (Truong and Ahn, 2012).

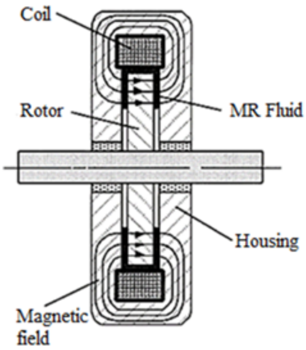


Fig. 5. Rotary MR fluid brake (Carlson and Jolly, 2000).

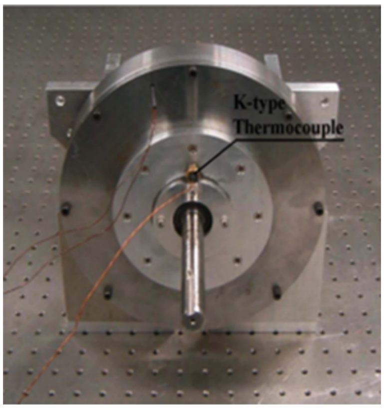


Fig. 6. (Color online) MR brake (Karakoc *et al.*, 2008).

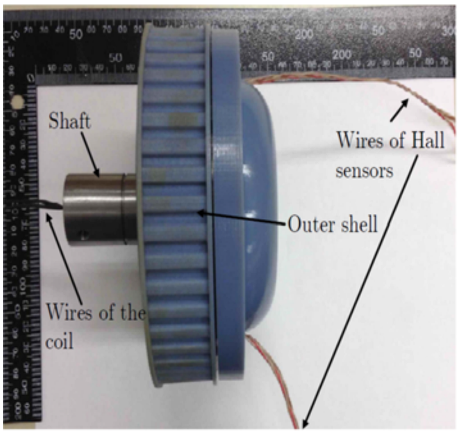


Fig. 7. (Color online) The optimally designed MR clutch (Moghani and Kermani, 2016).

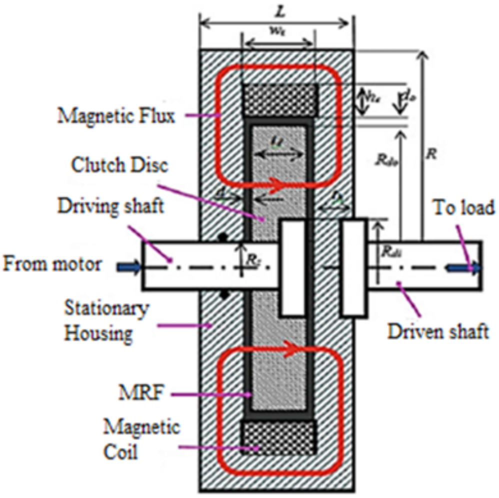


Fig. 8. (Color online) MR clutch (Nguyen *et al.*, 2016).

4. Types of MR Damper

According to the design and configuration of MR dampers, basically MR damper can be divided into three classifications, monotube, twin tube, and double-ended MR damper along with MR- Hydraulic hybrid damper. Monotube MR damper consists of only one tube or reservoir is known as Monotube MR damper as presented in Fig. 22.

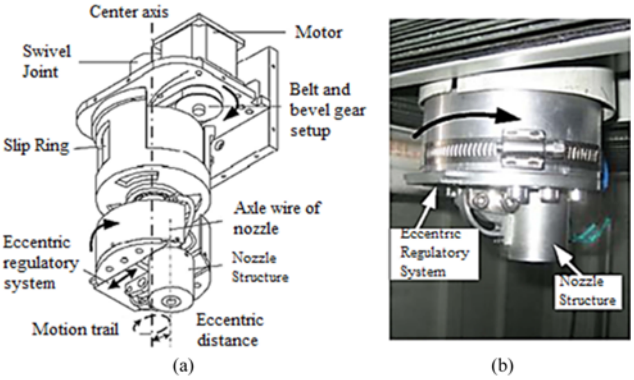


Fig. 9. (Color online) (a) 3D CAD view of polishing experimental setup and (b) main hardware with different components (Wang *et al.*, 2013).

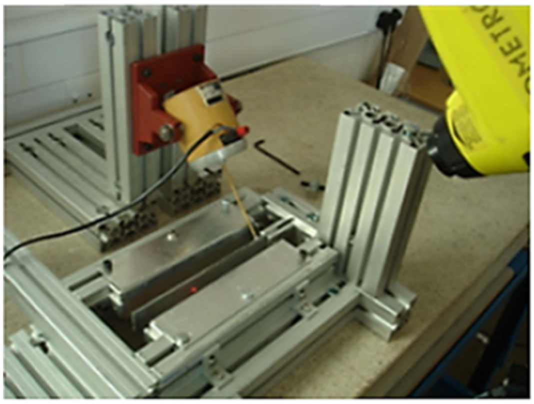


Fig. 12. (Color online) MR beam configurations test rig with vertical (Lara-Prieto *et al.*, 2009).

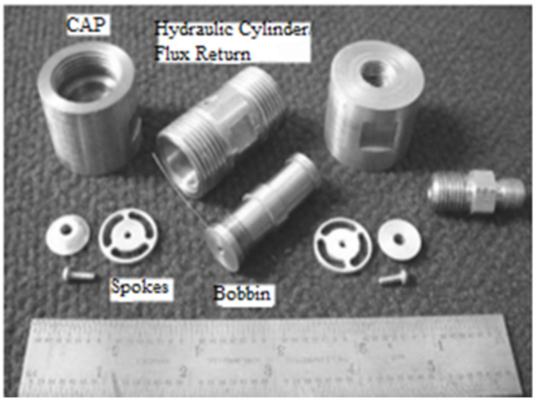


Fig. 10. MR hydraulic valve (Yoo and Wereley, 2004).

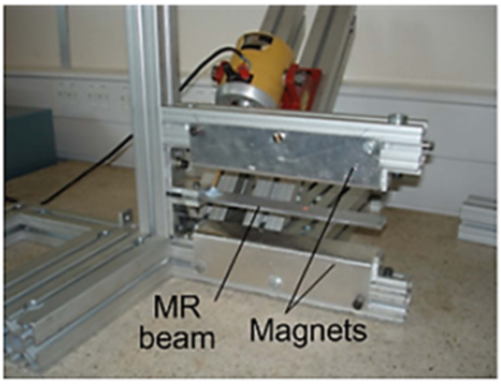


Fig. 13. (Color online) MR beam configurations test rig with horizontal (Lara-Prieto *et al.*, 2009).

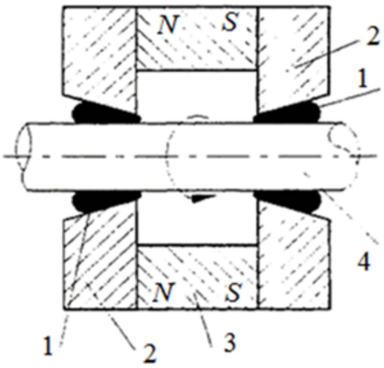


Fig. 11. MR seal (1) MR fluid, (2) poles, (3) permanent magnet, and (4) magnetic shaft (Kordonski and Gorodkin, 1996).

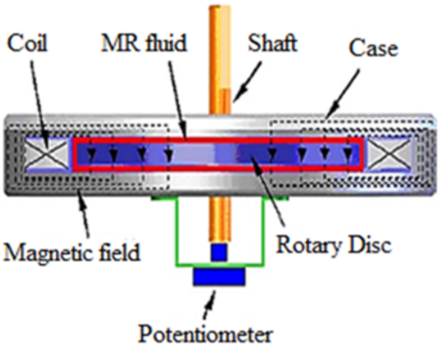


Fig. 14. (Color online) Position-feedback MR actuator (Liu *et al.*, 2006).

Among these three types it is most commonly used due to its compact size and ability to install in any location. In addition, an MR damper that contains two fluid reservoirs is called twin tube MR damper where one tube is inside of the other, as displayed in Fig. 23.

Moreover, the MR damper in which two piston rods of the same diameter enter the reservoir from both ends of the damper is known as double ended MR damper as displayed in Fig. 24 (a section view). It is a type of damper where the volume is unchanged due to piston's respective movement and as a result, the accumulator mechanism is absent here. Some common application of this damper is in gun recoil (Ahmadian and Poynor, 2001), bicycle (Ahmadian *et al.*, 1999), building sway motion controlling due to heavy wind flow or earthquakes etc.

However, the most recent category of MR damper is

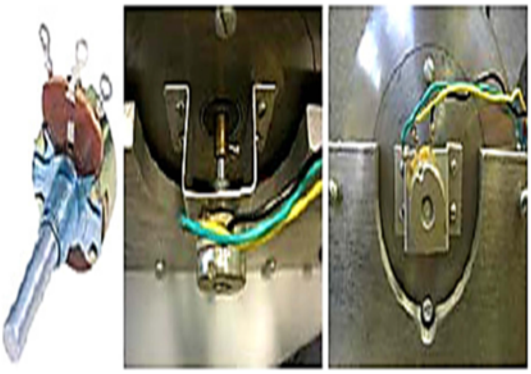


Fig. 15. (Color online) The linear potentiometer (Liu *et al.*, 2006).

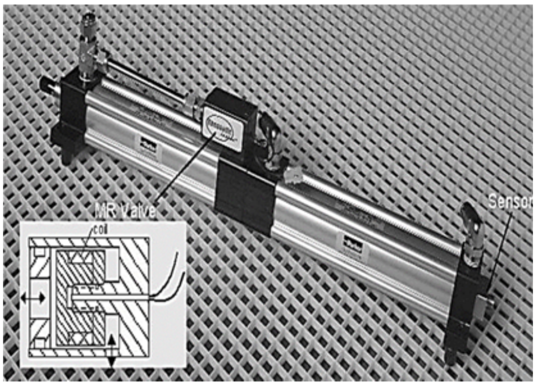


Fig. 16. Tandem pneumatic actuator with MR fluid in flow (Jolly, 2001).

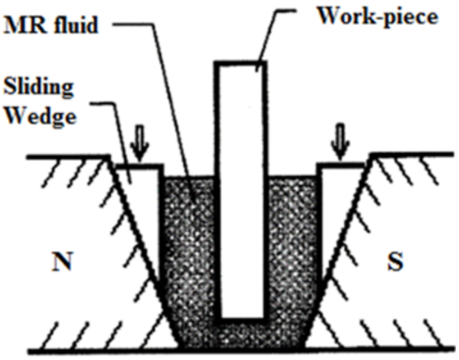


Fig. 17. The MR-fluid-flexible-fixture device (Tang *et al.*, 1999).

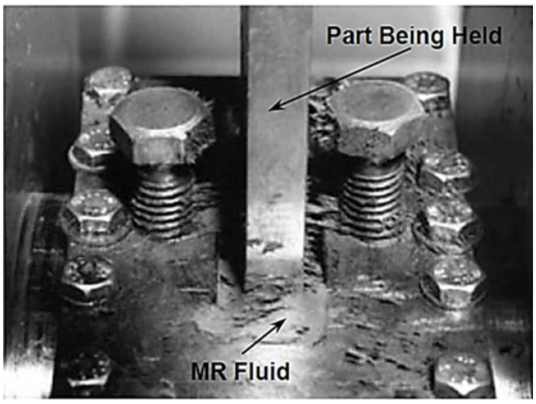


Fig. 18. Flexible MR fluid fixture in use (Poynor, 2001).

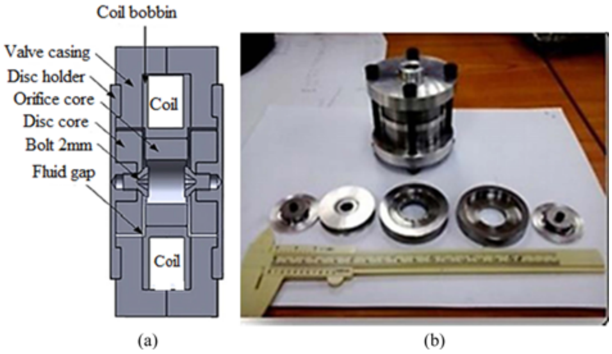


Fig. 19. (Color online) (a) Module cross-section view and (b) MR valve (Ichwan *et al.*, 2016).

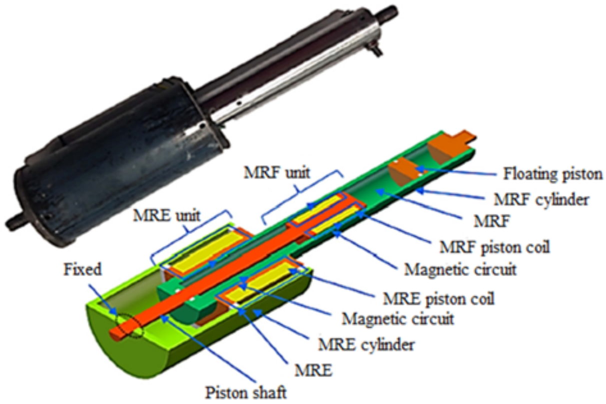


Fig. 20. (Color online) Structure schematic and photograph of the MRE-F isolator (Sun *et al.*, 2016).

called MR piloted hydraulic damper as exhibited in Fig. 25. It is hybrid damper where a small MR damper controls a valve that is used in turn to control the flow of hydraulic fluid.

Various arrangements of basic functioning apparatuses (*i.e.* MRF cylinder and MRF control valve, coil number, mode type, and piston stages), separated MRF dampers into a number of classifications. Besides, considering the coil layout in MR fluid control valve, monotube MR fluid dampers have two categories such as internal coils MR fluid dampers and external coils MR fluid dampers as shown in Figs. 26 and 27. The advantage of MR damper with external coils is that the generated heat cannot heat the damper's hydraulic system (Hitchcock *et al.*, 2002). But, it has a damping force below the internal coil MR damper (Grunwald and Olabi, 2008).

According to the MR control valve (coil wires and its

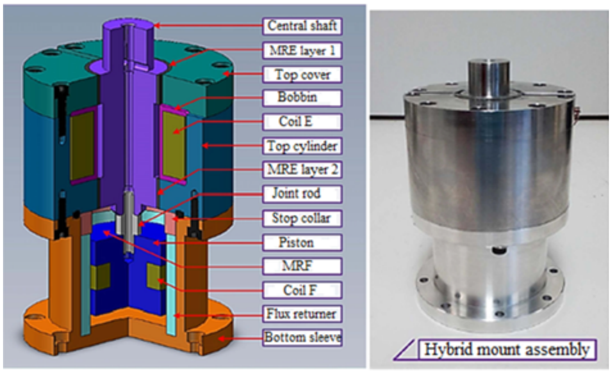


Fig. 21. (Color online) Schematic of magnetorheological elastomer-fluid (MRE-F) isolation mount design (Xing *et al.*, 2016).

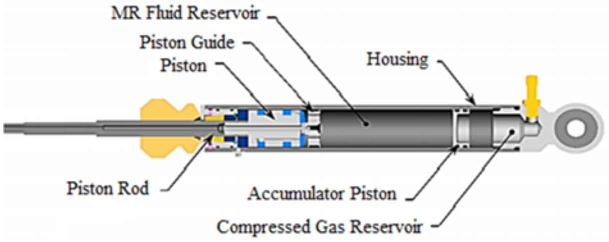


Fig. 22. (Color online) Mono tube MR damper (Poynor, 2001).

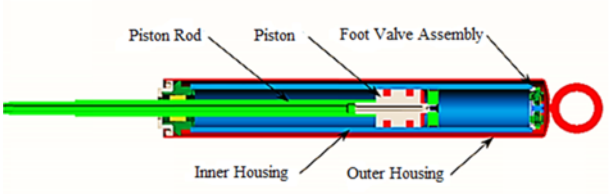


Fig. 23. (Color online) Twin tube MR damper (Poynor, 2001).

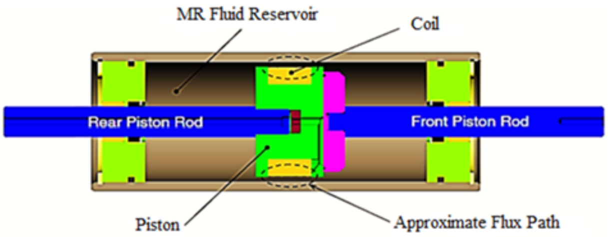


Fig. 24. (Color online) Double ended MR damper (Poynor, 2001).

separation from MRFs) placement inside the moving piston and piston rod, the MR dampers are classified as single flow mode, mixed mode, and multimode. Actually, mixed mode is a combination valve mode and direct shear mode, whereas in multimode valve mode, direct shear mode and squeeze mode are used. In flow mode, the pressure difference causes MR fluid to flow from one concentric surface to another as shown in Fig. 28a. Moreover, in shear mode MR damper in Fig. 28b, this MR fluid flows from one moving surface to other. But, in the case of squeeze mode MR damper as shown in Fig. 28c, fluid in the altitude flow channel differs in a parallel direction with regards to the magnetic field and whether the fluid will be squeezed out or into the flow channel depends on the distance between the opposing surfaces.

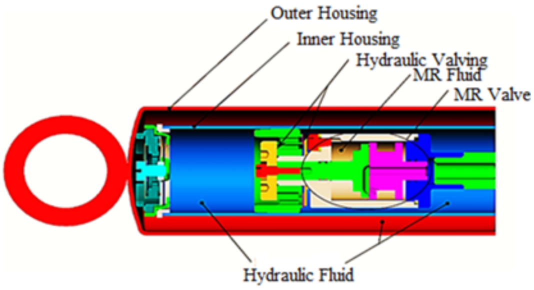


Fig. 25. (Color online) MR- hydraulic hybrid damper (Poynor, 2001).

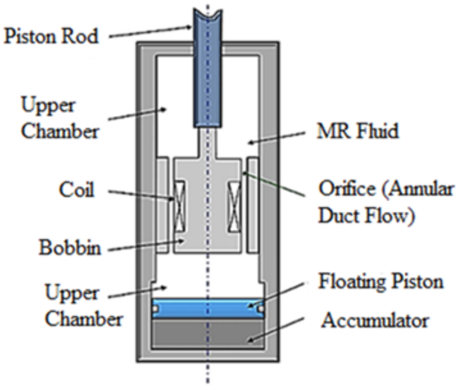


Fig. 26. (Color online) MRF damper with internal coils (Sohn *et al.*, 2015).

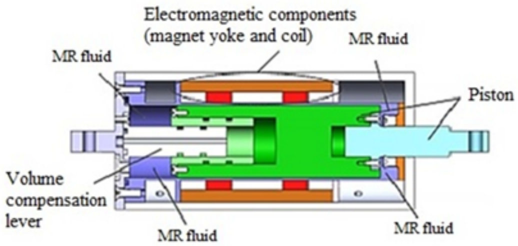
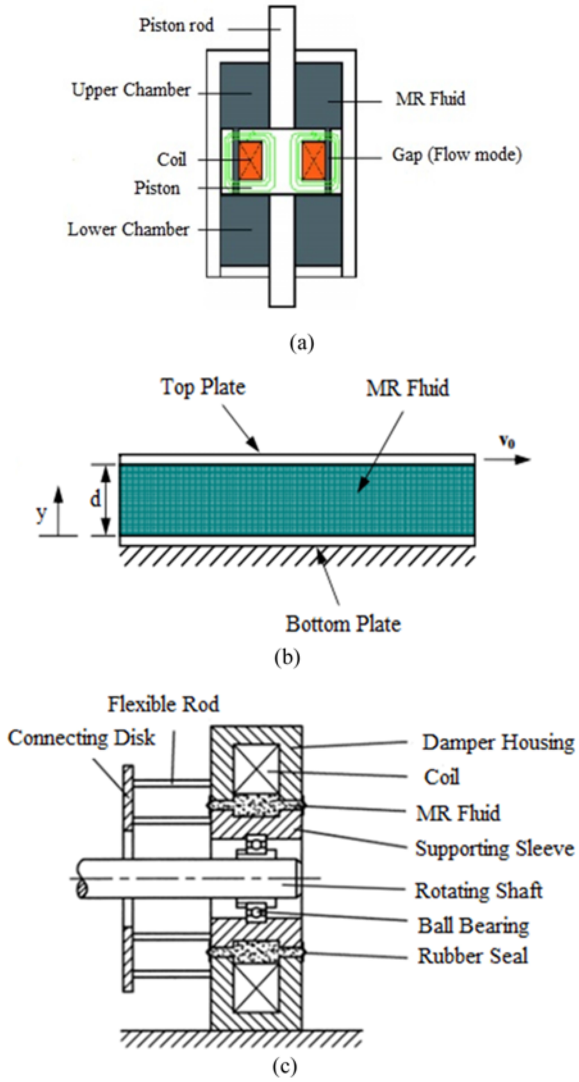


Fig. 27. External coils based MR fluid damper (Hong *et al.*, 2015).

Besides, Fig. 29 displays the design of an MR fluid damper which is a combination of shear and squeeze working modes. Usually, the mixed mode MR damper produces higher damping force compare to single mode MR damper (Yazid *et al.*, 2014; Zeinali *et al.*, 2016). In addition, a multimode isolator structural design has shown in Fig. 30. In multimode isolator, when the top elastomer is moving, the valve and shear model damping create inside the outer cylinder where the electromagnetic coil attached



(a)

(b)

(c)

Fig. 28. (Color online) (a) Flow mode MR damper (Kim *et al.*, 2016), (b) shear mode MR damper (Wereley *et al.*, 2008), and (c) squeeze mode MR damper (Wang *et al.*, 2003).

with the top elastomer. Besides, due to the axial motion between the elastomer and bobbin, the squeeze mode damping is formed.

The MR damper's damping force increases with the increment of activation area (the area of MR fluid that activated by a magnetic field). So, with the increasing of coil stage of the piston (increases the activation area of MR fluid by a magnetic field) the damping force will be increased (Poynor, 2001). In relation to the coils stage of piston, the MR dampers are classified into single coil MR damper, double coil MR damper, triple coil MR damper, and multi-coil MR damper. The single coil MR damper has shown in Fig. 31. Figure 32 displays a double stage piston or double coil MR damper and Fig. 33 shows a triple stage piston MR damper. Moreover, a multi coil MR damper has shown in Fig. 34 which can generate a maximum force of 4 kN, at 10 amps of current.

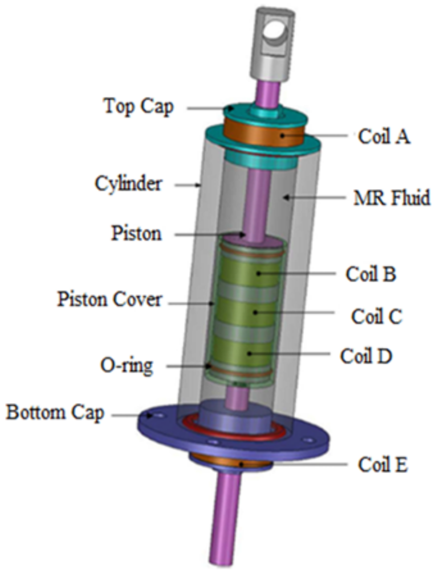


Fig. 29. (Color online) Mixed mode MRF damper (Yazid *et al.*, 2014).

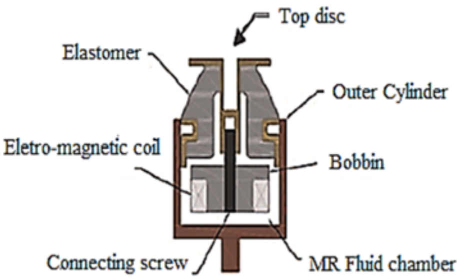


Fig. 30. (Color online) Multimode MR isolator (Brigley *et al.*, 2007).

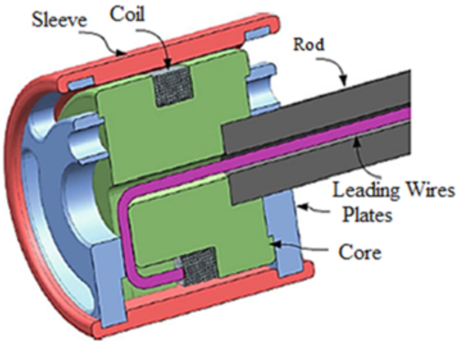


Fig. 31. (Color online) Single coil MR damper (Gołdasz and Sapiński, 2015).

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 damper. In rotary MR damper, the MRF operates in one or two flow mode inte-

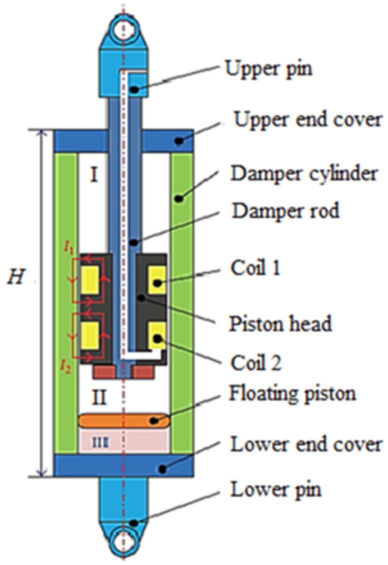


Fig. 32. (Color online) Double coil MR damper (Hu *et al.*, 2016a).

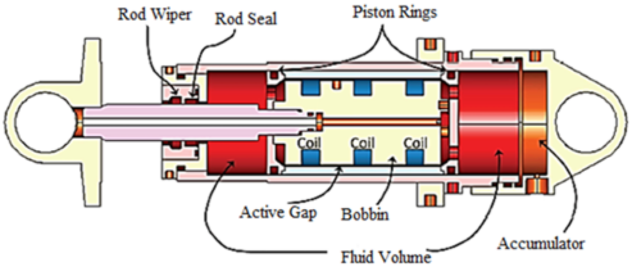


Fig. 33. (Color online) Triple coil MR damper (Wilson *et al.*, 2013).

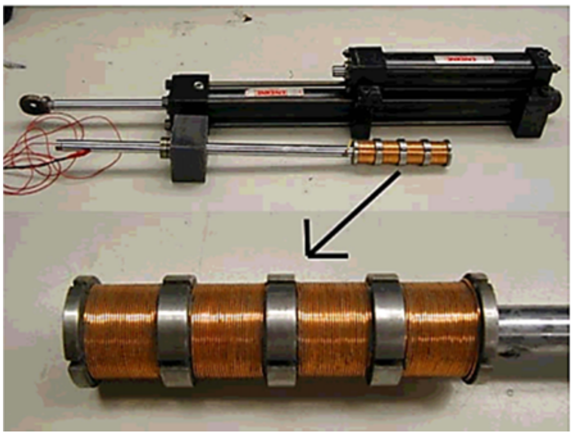
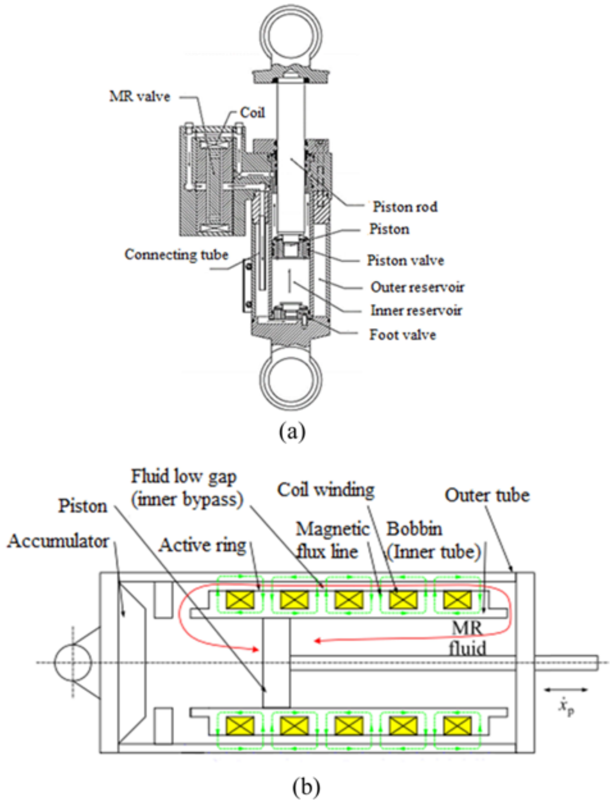


Fig. 34. (Color online) Multi-coil MR damper (Gavin *et al.*, 2001).



(a)

(b)

Fig. 35. (Color online) (a) MR damper with external bypass (Guo *et al.*, 2015) and (b) MR damper with inner bypass (Bai *et al.*, 2015).

grally. With regards to design and configuration, there exist two styles of rotary MR damper and they are known as continuous angle and limited angle revolution MR damper (Imaduddin *et al.*, 2013).

According to the valve location, MR dampers are separated into two categories, such as internal valve MRF damper and external valve or bypass valve MRF damper. In the internal valve MRF damper device, the valve usually attached to a piston inside the MRF damper and it regulates MR fluid's flow rate across the piston. On the other hand, MRF damper with bypass valve has a perfectly sealed piston and the bypass channel outside the damper is used for MR fluid flow. Simplicity in assembly, easy maintenance, and reduction of induced temperature from the coil to the MR fluid are some major advantages of bypass valve based MR damper (Zhu *et al.*, 2012). Moreover, it can apply for a different purpose without modifying the damper structure. Figure 35 shows MR damper with bypass valve. Moreover, Fig. 36 displays a bypass rotary MR damper.

Besides these all classification MR damper can more divided into some other types such as syringe-type MR damper, sponge-type MR fluid damper, and MR squeeze-film damper. A syringe-type MR damper has shown in Fig. 37. This syringe type MR damper consists of MR fluid into the straight flow channel, an electromagnetic coil which is coiled outside straight flow channel, and a piston and piston rod is situated at the terminal of each side of the flow channel (Tong and Huang, 2014). This change not only increases the length of the flow channel,

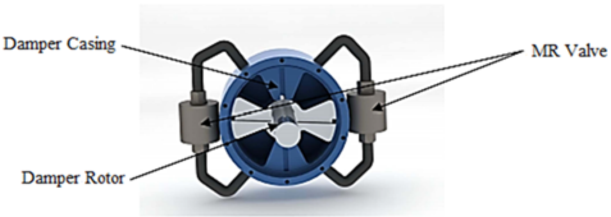


Fig. 36. (Color online) Bypass rotary MR damper (Imaduddin *et al.*, 2014).

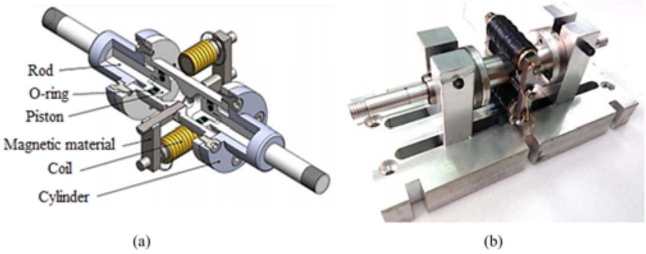


Fig. 37. (Color online) (a) 3D drawing of syringe-type MRF damper and (b) syringe-type MR damper (Tong and Huang, 2014).

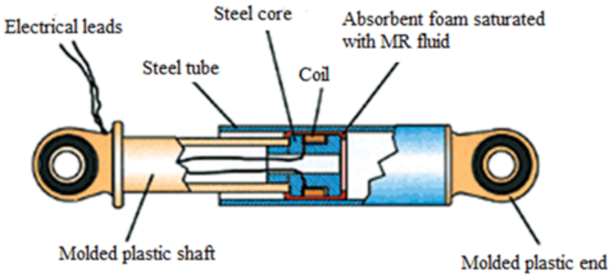


Fig. 38. (Color online) MR sponge damper (Carlson, 2002).

but also changes the excitating paramagnetic particles direction to be vertical with the direction of flow and thus increases the ultimate shear strength of MRF. Moreover, they are capable of generating a concentrated damping force of 153N without applying a magnetic field (Tong and Huang, 2014). Furthermore, in sponge type MR damper as presented in Fig. 38, the MR fluid holds a spongy matrix and it operates in shear mode with less difficulty and seal problems. This types of MR damper have two forms (expulsion and extraction) and usually used in a number of applications especially in mechanical engineering such as washing machines.

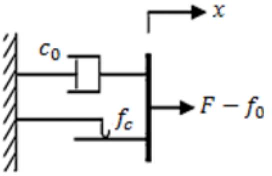
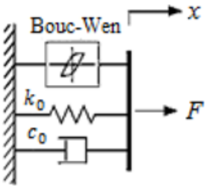
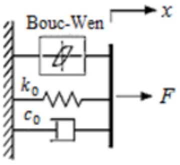
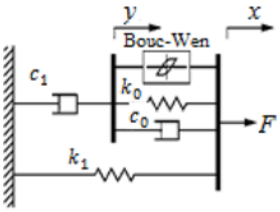
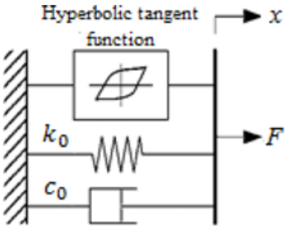
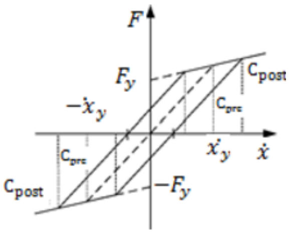
5. Models Classifications for MR Dampers

According to the method of modeling, MR damper's models might be classified as parametric dynamic models or non-parametric dynamic models and can be further categorized as quasistatic models or dynamic models with regards to their properties. Moreover, considering the reversibility the models may possibly be seperated as dynamic and inverse dynamic models. Various methods have been suggested for finding MR damper models, recognizing their parameters and generating self-powered MR damper models. A few techniques have been suggested throughout the years for getting MR damper models and distinguishing their parameters. Taking into account the Bingham plastic model for MR fluid, Bingham model for MR damper has been proposed (Stanway *et al.*, 1996). This model has a Coulomb friction element which is positioned in parallel with regards to a viscous damper, as shown in Table 5. Beyond the yield point, this model is used for measured MR fluid behavior. In any case, the fluid's rigidness is expected in the pre-yield area. Therefore, in deformations and low shear rates, this model is not capable of defining the elastic properties of the fluid, that are required for dynamic applications (Kamath and Wereley, 1997).

Moreover, to model hysteretic system Bouc-Wen model is widely used because this model can mathematically control. Moreover, Bouc-Wen model is particularly useful and can display a comprehensive range of hysteretic behavior. In 1976 Wen modified the hysteresis model of Bouc which has an attractive mathematical ease. Moreover, it has the capability to characterize the huge type of hysteretic behavior (Ismail *et al.*, 2009). To simulate the hysteresis loops, the Bouc-Wen model can use broadly because it keeps the force versus displacement and force versus velocity characteristics of the MR dampers (Wang and Liao, 2011). Nevertheless, Bouc-Wen model's nonlinear force and velocity response do not roll-off like Bingham model in the yield region. In addition, by 1997 Spencer *et al.* suggested a revised form of the simple Bouc-Wen model to better guess the MR damper response for a variety of inputs. This modified phenomenological MR damper model has shown in Table 5, which increases the accuracy. The major limitations of this model ascend from potential impreciseness because of the expected linear existing property and identification problem of a huge number of parameters.

On the other hand, in 2006 an MR damper model based on hyperbolic tangent function was proposed by Kwok *et al.*, as shown in Table 5. The idea was to use a hyperbolic tangent function to signify the hysteresis, and linear function to show the stiffness and viscosity. Wang and Liao (2011) referred to this model as "computationally efficient" from the perspective of parameter identification as well as following the addition of controller design and application. Furthermore, Stanway *et al.* (1996) developed the nonlinear biviscous model and assumed the MR fluids behavior as plastic for not only in the pre-yield region but also in the post-yield region. However, as the acknowledged damping rates have a relationship only with a specific excitation, the response does not effectively work in the situations where the excitation varies.

Table 5. Various MR damper models.

Model	Equation	Figure	References
Bingham model for MR damper	$F(t) = c_0\dot{x} + f_c\,\mathrm{sgn}(\dot{x}) + f_0$ c_0 = damping coefficient f_c = frictional force f_0 = offset force		(Kamath and Wereley, 1997; Spencer *et al.*, 1997; Stanway *et al.*, 1996)
Bouc-Wen hysteresis operator based model	$F(x, \dot{x}) = g(x, \dot{x}) + \alpha z(x)$ $\dot{z} = -\gamma\lvert\dot{x}\rvert z\lvert z\rvert^{n-1} - \beta\dot{x}\lvert z\rvert^{n} + A\dot{x}$ $g(x, \dot{x})$ = nonhysteretic component $z(x)$ = hysteresis component $\dot{z}$ = time derivative		(Ismail *et al.*, 2009; Wang and Liao, 2011)
Simple Bouc-Wen model	$F(t) = c_0\dot{x} + k_c(x-x_0) + \alpha z$ c_0 = damping coefficient k_0 = spring coefficient x_0 = initial deflection z = evolutionary variable		(Spencer *et al.*, 1997)
Modified Bouc-Wen model	$F(t) = c_1\dot{y} + k_1(x-x_0)$ $\dot{y} = \frac{1}{(c_0-c_1)}[\alpha z + c_0\dot{x} + k_0(x-y)]$ $\dot{z} = -\gamma\lvert\dot{x}-\dot{y}\rvert\lvert z\rvert^{n-1}z - \beta(\dot{x}-\dot{y})\lvert z\rvert^{n} + A(\dot{x}-\dot{y})$		(Spencer *et al.*, 1997)
Hyperbolic tangent function based models	$F(t) = c_o\dot{x} + k_o x + \alpha z + f_0$ $z = \tanh[\beta\dot{x} + \delta\,\mathrm{sgn}(x)]$		(Kwok *et al.*, 2006)
Nonlinear biviscous models	$F(t) = \begin{cases} C_{post}\dot{x} + F_y & (\dot{x} \ge \dot{x}_y) \\ C_{pre}\dot{x} & (-\dot{x}_y \ge \dot{x} \ge \dot{x}_y) \\ C_{post}\dot{x} - F_y & (\dot{x} \le -\dot{x}_y) \end{cases}$		(Wang and Liao, 2011)

6. Energy Harvesting Magneto-Rheological Fluid Damper System

The energy generation technology from MR damper would be able to enhance the reliability of total MR damper systems. Huge advantages of this system include the reduced weight and size, easy way of conservation, and little maintenance cost. Generally, MR damper is activated by supplying power to the coil with the help of a power supply and sometimes a current amplifier as well for various applications. The wasted energy from various vibration and shock motion can easily be converted into mechanical energy and there are many processes to convert this energy from mechanical to electrical form. By utilizing this electrical energy MR damper system with power generation ability has developed. This self-power MR damper system is very useful in big civil constructions since providing external power supply system is very complex.

6.1. Energy harvesting by permanent magnet and coil arrangement

An electromagnetic induction (EMI) device is attached to the MR damper to generate energy which is introduced by Cho *et al.* (2005; 2007). The EMI device consists of a permanent magnet and a coil. This EMI device can generate electrical energy from mechanical vibration energy and generated energy can supply into MR damper's coil. The schematic structure of their proposed MR damper is exposed in Fig. 39 and model is expressed by the Eqs. (1) and (2).

$$f = c_1\dot{y} + k_1(x - x_0)\,, \tag{1}$$

$$\dot{y} = \frac{1}{(c_0 + c_1)}[\alpha z + k_0(x - y) + c_0\dot{x}]\,. \tag{2}$$

Moreover, Jung *et al*. designed a large scale EMI system based smart MR damper to generate energy and evaluated its performances experimentally (Jung *et al.*, 2008; Kim *et al.*, 2010). The EMI system has permanent magnet and coil arrangement displayed in Figs. 40 and 41, which can generate energy from reciprocal motions. According to the Faraday's law, the generated voltage from the EMI system is linearly proportional to the relative velocity across the MRF damper. The experimental results show that this EMI system can provide a sensing capability that is useful in the MRF damper-based control systems and the EMI can work as an input power source for damper (Kim *et al.*, 2010).

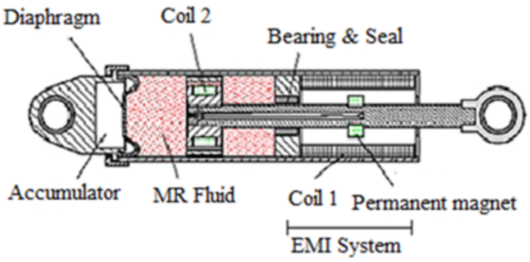


Fig. 39. (Color online) Schematic of a smart passive MR damper system (Cho *et al.*, 2005).

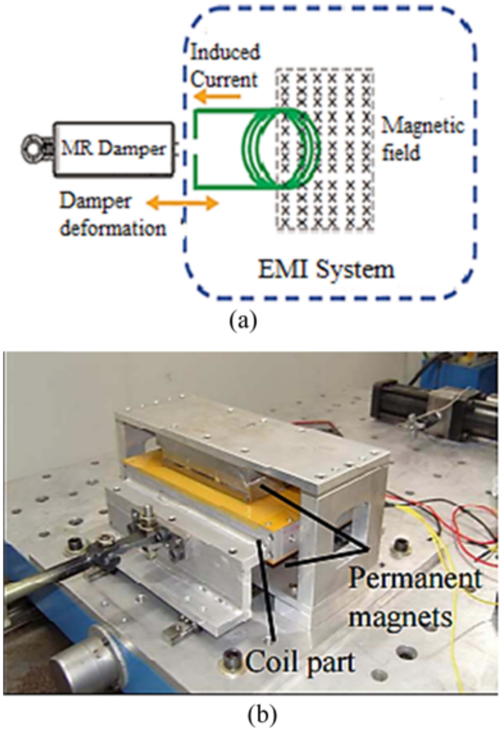


Fig. 40. (Color online) (a) Schematic of EMI system with MR damper and (b) large scale EMI system (Jung *et al.*, 2008).

Chen and Liao (2012a) designed an energy generation system in MR damper which consists multi-pole (each pole pair has one permanent magnet, coil, and pole piece) power generator. In addition, this proposed designed has the self-sensing capability that combines energy generation and dynamic sensing damping technology into one device, as displayed in Fig. 42. Figure 43 exhibits the prototype of that MR damper.

The experiment result of this MR damper model has shown that it has sufficient power production and velocity sensing abilities relevant to different dynamic methods. The size of this model is large so it is suitable for double-

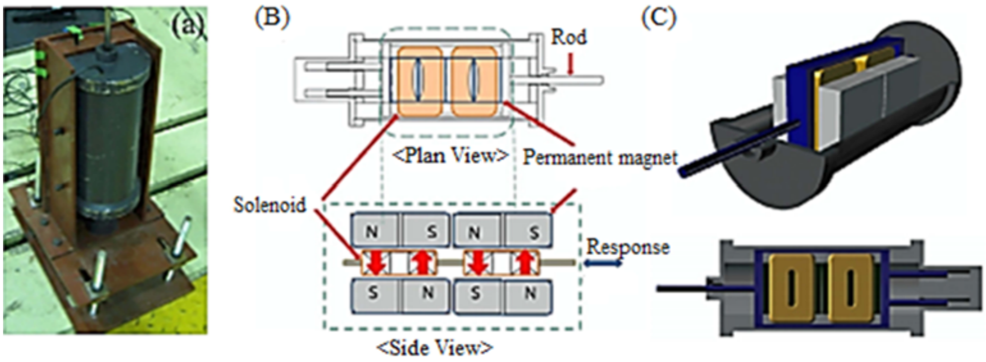


Fig. 41. (Color online) Proposed EMI system based MR damper: (a) Prototype, (b) schematic configuration, and (c) 3D section view (Kim *et al.*, 2010).

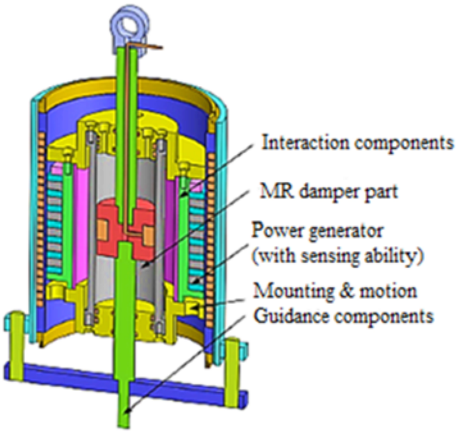


Fig. 42. (Color online) Sectional view of a self-sensing and self-powered MR damper (Chen and Liao, 2012a; 2012b).

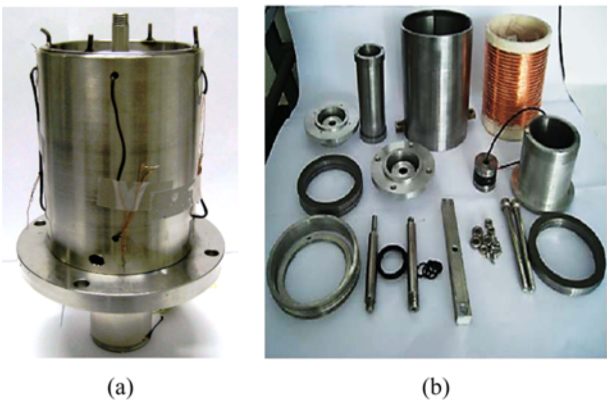

(a) (b)

Fig. 43. (Color online) Images of fabricated prototype: (a) Developed assembled prototype and (b) prototype's disassembled parts (Chen and Liao, 2012a).

ended MR damper construction and applicable in civil structures.

Three years later, Chen *et al.* (2015) again proposed another energy generated MR damper which is known as a regenerative magnetorheological damper. Compared to the previous model, this proposed design has additional spring. The proposed model has shown in Fig. 44.

Sapiński (2010) developed and experimentally tested a power generator for linear MR damper. The generator has permanent magnets and coils with foil winding. Figure 48 displays the structure of the power generator and Fig. 45 shows the prototype of the power generator. The device produces electrical energy which is delivered to the MR damper in order to verify the damping characteristic. The device can change the MR damper's reciprocal motion into kinetic energy which has seen from experimental results. That is the reason the generator might be utilized to develop vibration control system utilizing MR damper without the requirement of any external power. The experimental setup with MR damper is exposed in Fig. 46. Later, they again developed the power generator known as electromagnetic power generator by changing permanent magnet (incorporating high-performance bulk magnets) and proposed an energy generation system (Snamina and Sapiński, 2011).

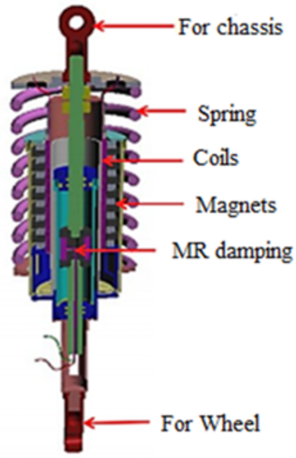


Fig. 44. (Color online) Cross-sectional view of the proposed regenerative MR damper (Chen *et al.*, 2015).

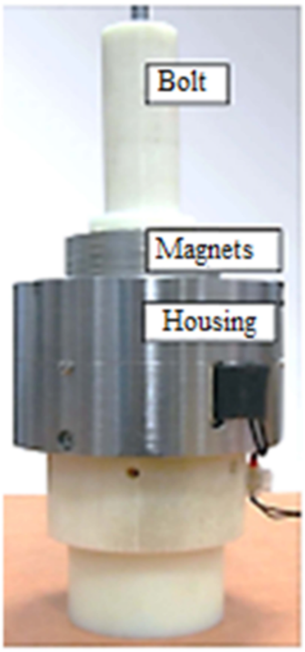


Fig. 45. (Color online) Prototype of the power generator (Sapiński, 2010).

Moreover, this system has a mechanical and electrical sub-system along with MR damper displayed in Fig. 47. The damping force generated by this model is expressed in the following Eq. (3). The generator is working as an energy source and the necessary energy is generated utilizing the vibrations. From this generated energy around

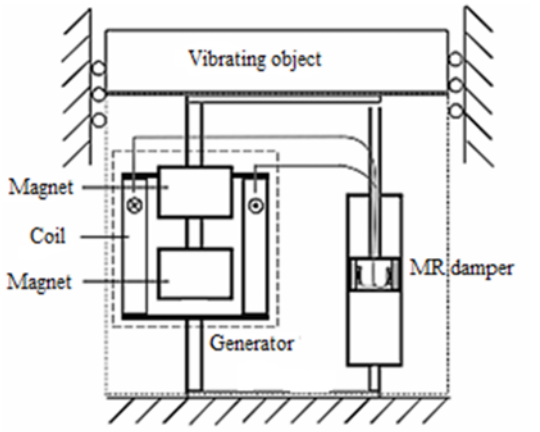


Fig. 46. Schematic diagram of the experimental setup (Sapiński, 2010).

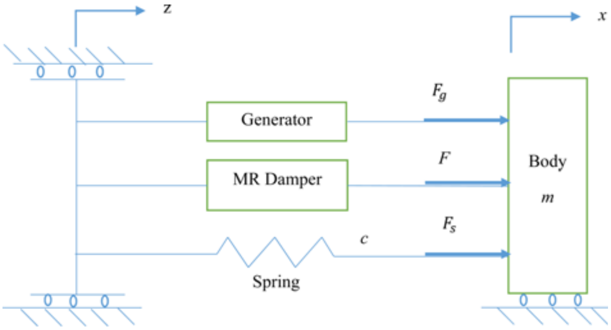


Fig. 47. (Color online) Schematic mechanical sub-system (Snamina and Sapiński, 2011).

2.5% is drained by the mechanical sub-system of the MR damper.

$$F = (c_1|i| + c_2)\tanh\left[\beta\left(\left(\frac{dz}{dt}-\frac{dx}{dt}\right) + p_1(z-x)\right)\right] + (c_3|i| + c_4)\left(\left(\frac{dz}{dt}-\frac{dx}{dt}\right) + p_2(z-x)\right) \quad (3)$$

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

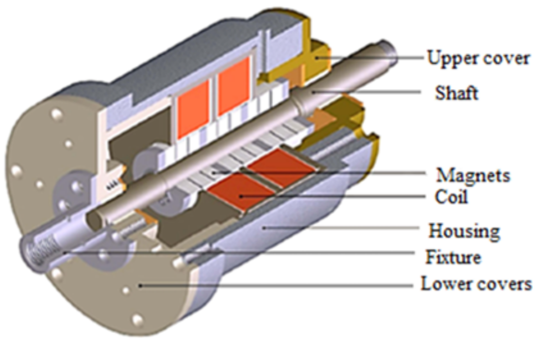


Fig. 48. (Color online) Structure of the power generator (Sapiński, 2014).

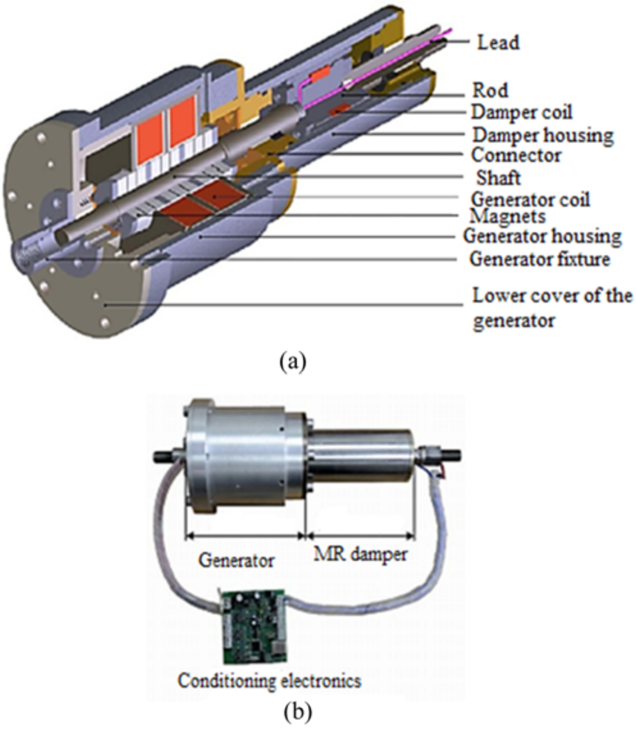


Fig. 49. (Color online) (a) Structure of the EH-L MR damper and (b) porotype of the EHL MR damper (Sapiński, 2014).

In addition, Sapinski (2014) again developed an energy harvesting system which consists of an MR damper, a power generator, and a conditioning electronics unit. The power generator as shown in Fig. 48 has three systems of permanent magnets (three magnets in each), two spacers (inner and outer), and two winding sections coil (273 turns each). Moreover, Fig. 49a displays the structure of the energy harvesting linear (EHL) MR damper and Fig. 49b shows the prototype of the energy harvesting linear (EHL) MR damper. The result obtained from experiments has shown good promise on the modeled characteristics. In this model, there is no necessity of external power supply as well as a sensor due to its self-powered and self-sensing capabilities. Moreover, the performance of the proposed energy generated MR damper system was evaluated in a single degree of freedom mechanical structure (Sapiński *et al.*, 2016). The experimental setup to evaluate the performance of the system has shown in Fig. 50.

Besides, Zhu *et al.* (2015) proposed an MR damper design where permanent magnets attached to piston rod and coil attached with damper outside cylinder to generate energy. The modeling of their proposed MR damper as shown in Fig. 51.

Moreover, Choi and Wereley (2009) established an MR damper with energy harvesting capability where the combination of a stator, a permanent magnet, and a spring

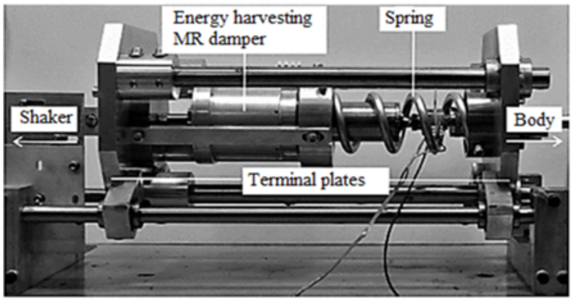
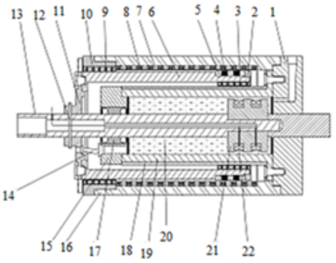


Fig. 50. Experimental setup of the proposed energy harvested MR damper system (Sapiński *et al.*, 2016).



1	Rear cap	9	Linear bushing 2	17	Linear bushing 3
2	Fixer	10	Front cap	18	Magnetic shield cylinder
3	Linear bushing 1	11	Fix cap of mover	19	Damper cylinder
4	Magnet	12	Pin	20	MR fluids
5	Magnetic pole	13	Piston rod	21	Piston
6	Mover cylinder	14	Hydraulic pipe	22	Electromagnetic coil
7	Power coil	15	Front cap of damper		
8	Spacer	16	Outer cylinder		

Fig. 51. Structure of the MR damper with power generator (Zhu *et al.*, 2015).

functions as an energy-harvesting dynamic vibration absorber (DVA), as shown in Fig. 52. In this damper model, two permanent magnets are attached with spring in the top of the piston head inside the MR damper and these magnets are surrounded by coils which are attached to piston rod. With the movement of piston rod, the magnet also moves and generates energy inside the coil. The generated energy is used directly supplied to the coils of MR damper and avoids the usage of extra sensors.

Moreover, another novel MR damper model with energy harvesting capability as shown in Fig. 53 was designed by Hu *et al.* (2016b) based on electromagnetic introduction (EMI) principle. In this new MR damper model, the power generator has added inside the MR damper. Eight pairs of permanent magnets are screwed with the shaft and two types of the coil (coil A and coil B) arrangements are attached inside the piston rod. The connected 0° and 180° phase coils are known as coil A and connected 90° and 270° phase coils are known as coil B. When the piston moves then coil arrangements also move along with piston and these coils cut the magnetic field of the permanent

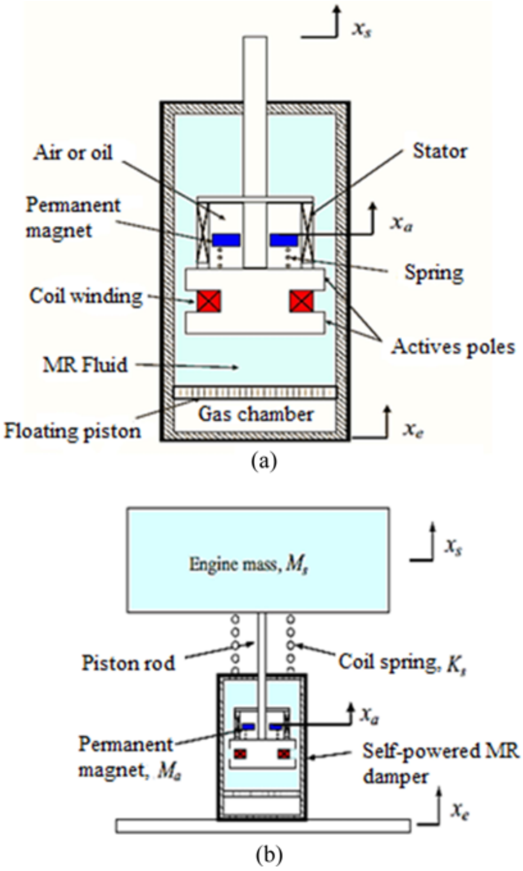


Fig. 52. (Color online) (a) Schematic diagram and (b) single-DOF engine mount system of self-powered MR damper (Choi and Wereley, 2009).

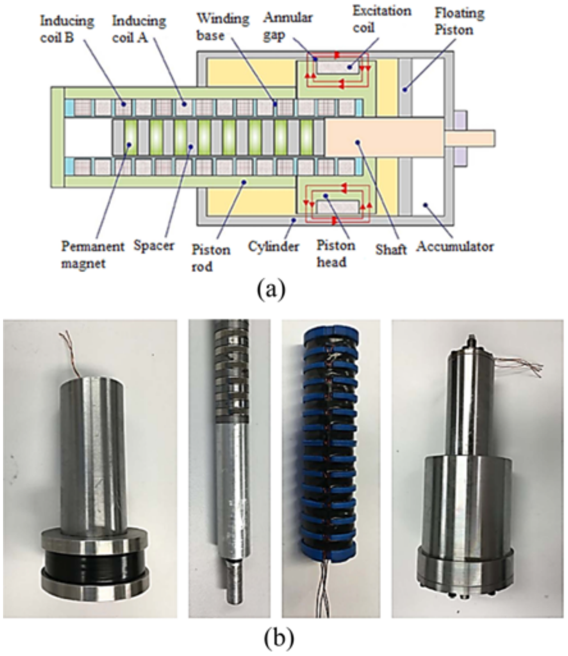


Fig. 53. (Color online) (a) Schematic diagram of the proposed MR damper and (b) prototype of the MR damper (Hu *et al.*, 2016b).

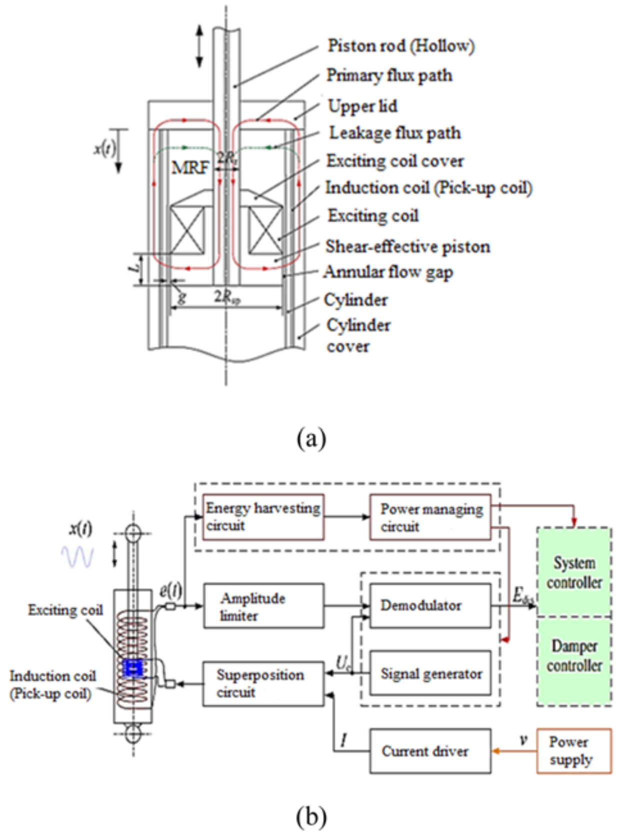


Fig. 54. (Color online) (a) Designed self-powered MR damper based on electromagnetic induction and (b) schematic of the proposed electronic system (Wang and Bai, 2013).

magnet which is attached with a screw inside the damper. When this interaction occurred between magnet and coil then electricity produces inside the coil A and coil B. It can generate about 1.0 V DC voltage at 0.06 ms^{-1} and can produce almost 750 N damping force at the current 0.6 A.

6.2. Energy harvesting by Induction coil

Wang and Bai (2013) proposed an MR damper model to generate energy by using induction coils only rather than using magnet and coil arrangement. This model proposed an integrated relative displacement sensor (IRDS) technology to convert MR dampers self-sensing with the help of electromagnetic induction. This proposed model comprises of an exciting coil convoluted around the piston and an induction coil curled on the nonmagnetic cylinder. The piston coil acts as the exciting coils of the MR fluid and wound coil of the cylinder acts as the induction coil of the model, as shown in Fig. 54. The prototype of the proposed model has shown in Fig. 55. This new method cuts the application cost of the MR damper.

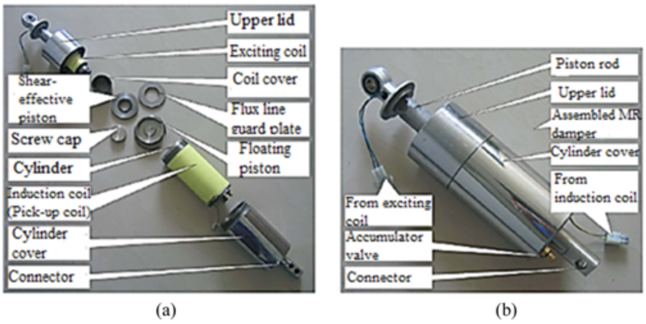


Fig. 55. (Color online) Prototype of the developed MR damper (a) before assembly and (b) after assembly (Wang and Bai, 2013).

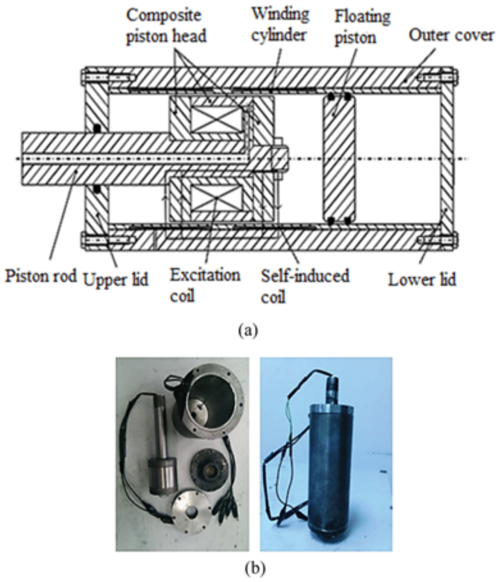
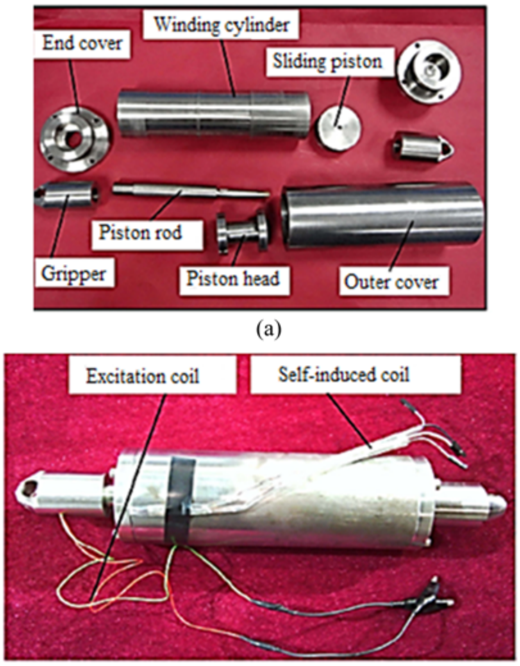


Fig. 56. (Color online) (a) Schematic of the DDSMRD and (b) prototype of the DDSMRD (Hu *et al.*, 2015a).

Moreover, another series of MR dampers with linear variable differential sensor (LVDS) were developed by Hu *et al*. (2015a; 2015b) which has self-sensing ability. Both proposed models are shown in Figs. 56 and 57 contains an exciting coil wounded around the piston and a differential induction coil wound on the nonmagnetic cylinder. When the input current applied inside the piston head coil, then it provides magnetic fields to both the linear variable differential sensor (LVDS) and MR fluids and some electromotive forces and the output voltage generated inside the differential induction coil. However, this model has application in the field of vehicle manufacture, bridge building, and so on. Schematic diagram of the projected MR damper's electronic system has shown in Fig. 58.

6.3. Energy harvesting by rack and pinion mechanism

Wang *et al.* (2009) presented MR damper with a sensing semi-active control system and energy harvesting ability. This system has a rack and pinion mechanism along with a linear permanent magnet used as DC generator, MR damper with current control capacity through a control circuit. An ideal active control system is designed using a



(a)

(b)

Fig. 57. (Color online) Prototype model of the proposed MR damper (a) different parts of the prototype and (b) after assembly (Hu *et al.*, 2015b).

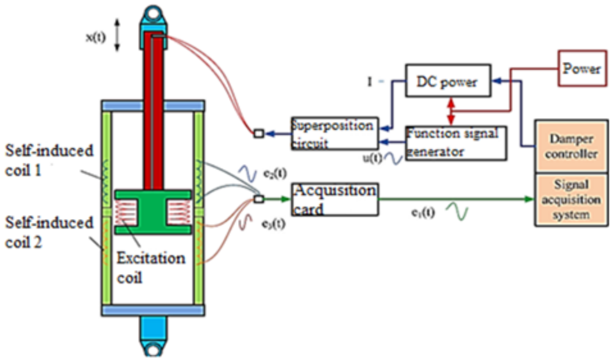


Fig. 58. (Color online) Schematic diagram of the proposed MR damper's electronic system (Hu *et al.*, 2015b).

linear quadratic regulator (LQR), where the LQR-dependent clipped optimal control along with skyhook control is utilized to regulate an MRF damper. Figure 59 shows the flowchart of their proposed model. The model is expressed by Eq. (4).

$$\dot{y} = \frac{1}{(c_0+c_1)}[\alpha z+k_0(x-y)+c_0\dot{x}]\,. \tag{4}$$

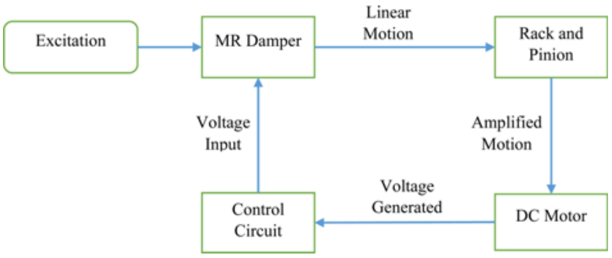
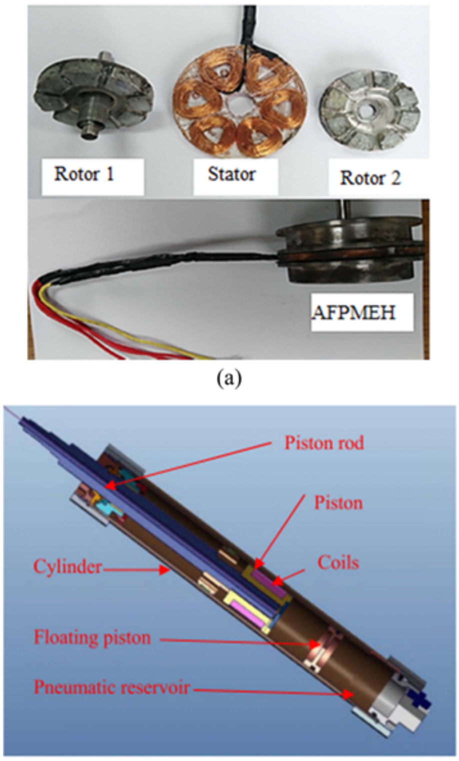


Fig. 59. (Color online) The flowchart of the control system with energy regeneration (Wang *et al.*, 2009).

The model has proved that, have similar control performance is observed in five different strategies such as one perfect active control, two semi-active controls, and two self-powered semi-active controls with respect to peer response and bearing response as well. The response is monitored by using only one accelerometer.

6.4. Energy harvesting by ball and screw mechanism

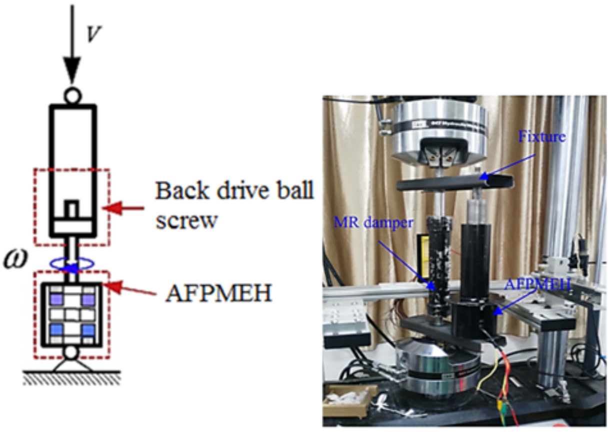
Dong (2015) proposed an axial flux permanent magnet energy harvester (AFPMEH) and examined it for a vehicle suspension system. The linear motion of the MR damper has changed to rotary motion of AFPMEH by back drive ball and screw mechanism. The proposed energy harvester as shown in Fig. 60a consists of two identical rotor (coreless) discs and a single stator. For this research there are six (four-layer) windings and eight poles are elected. Every rotor has eight number of permanent magnets (NdFeB) and these magnets are supported by iron disc. Moreover, the proposed MR damper can work with hybrid mode



(a)

(b)

Fig. 60. (Color online) (a) Picture of the AFPMEH and (b) schematic diagram of the proposed MR damper (Dong, 2015).



(a) (b)

Fig. 61. (Color online) (a) Schematic of the MR damper and AFPMEH setup and (b) experimental setup (Dong, 2015).

(valve and shear mode together) as shown in Fig. 60b. The full experimental setup has shown in Fig. 61. Further, in B grade road this energy harvester can generate about 2 W when velocity is around 0.1668 ms^{-1} but in D grade road the generated energy is about 45W when velocity is around 0.6693 ms^{-1} (Dong, 2015).

6.5. Energy harvesting by using generator and motor

Chu *et al*. (2016) designed an energy harvested MR damper which has controllable damping along with energy generation mechanism into one device. Their MR damper's energy harvesting part has a unique mechanism of transforming the linear motion into rotary motion, which has better stability and cost-effectiveness in comparison with other mechanical transmissions. A sectional view of the regenerative MR damper has exhibited in Fig. 62. A Maxon motor (as shown in Fig. 64) works as a power generator and effectively converts energy from mechanical to electrical, which is sufficient enough for supplying power to MR damper. It has several advantages over conventional approaches, like as it is an integrated device, comparatively light weight, easy to install and less maintenance is needed. Figure 63 shows their proposed MR damper with damping and power generation parts. Moreover, it has application in the field of vehicles, smart prostheses, in various civil constructions like bridges and buildings.

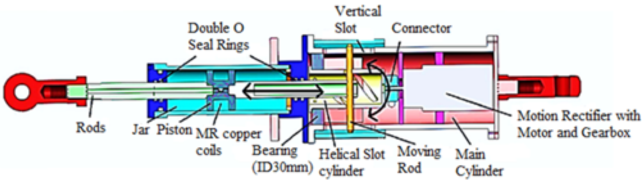
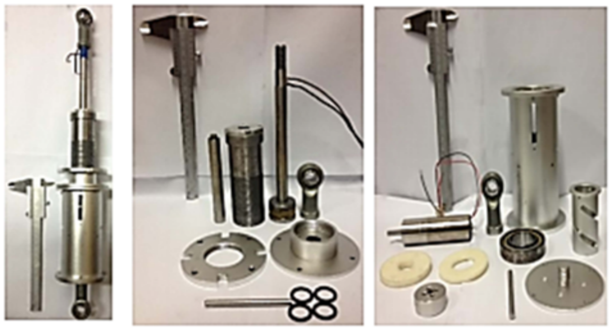


Fig. 62. (Color online) Sectional view of the energy harvesting MR damper (Chu *et al.*, 2016).



(a) (b)

Fig. 63. (Color online) Images of energy harvesting MR damper. (a) Prototype and (b) disassembled parts of MR damper and power generator (Chu *et al.*, 2016).

Fig. 64. (Color online) Image of motion rectifier prototype mounted with ZGA 25RP motor (Chu *et al.*, 2016).

On the other hand, Xinchun *et al.* (2015) proposed a novel magnetorheological (MR) damper which has energy harvesting capability. The system has ball-screw mechanisms for harvesting energy from vibration. Moreover, external vibration energy is converted into electricity energy with the help of a rotary permanent magnet DC generator. The developed self-powered MR has shown in Figs. 65 and 66 shows the prototype of the projected MRD. Furthermore, from experiment, it is observed that the MR damper's damping force is possible to use with good self-flexibility for both direct supply and rectified supply mode. This damper can save energy with less maintenance cost.

Wang *et al.* (2012) investigated a new energy harvesting device which has impeller and generator combinations to generate energy from fluid damper. The MR fluid was used as an example of fluid damper in this investigation and the energy generation system from MR damper has shown in Fig. 67. Moreover, Yu *et al.* (2014) proposed a new MR damper based on energy-harvesting device system. Actually, both two research the energy harvesting systems were proposed for the wireless sensor system. The whole system has an energy-harvesting device, an energy-management circuit, wireless sensor node, and MR damper. The energy-harvesting device as shown in Fig. 68 consists of an electromagnetic energy converter, an impeller, and a sealing unit where electromagnetic energy converter and impeller are coaxially connected.

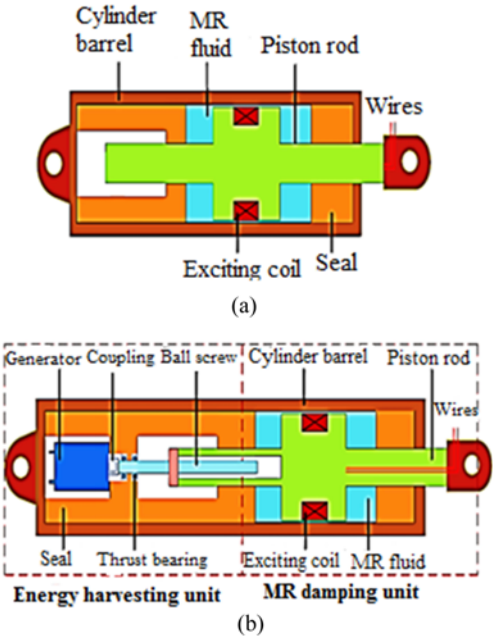


Fig. 65. (Color online) Two different assemblies of the double-ended MRD. (a) The conventional MRD and (b) the self-powered MRD (Xinchun *et al.*, 2015).

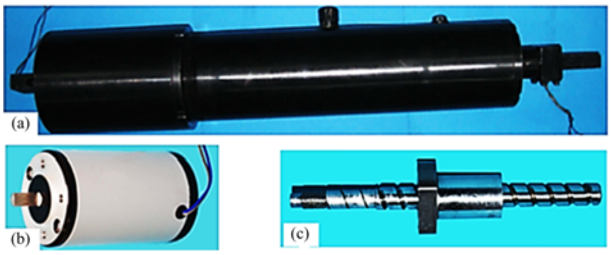


Fig. 66. (Color online) Photographs of the proposed MRD. (a) MRD, (b) the generator, and (c) the ball screw (Xinchun *et al.*, 2015).

With the movement of piston head inside the damper, the MR fluid also moves and it changes the velocity direction. Furthermore, with the changing of the movement of the MR fluid flow the impeller induces torque and rotates. The electromagnetic energy converter performs with the impeller running and generates electric energy.

Therefore, this device can generate the electrical energy used by wireless sensor node with the assistance of an energy management circuit. Also, it has seen that the energy harvester has no effect with regards to the increment of applied current to the MR damper.

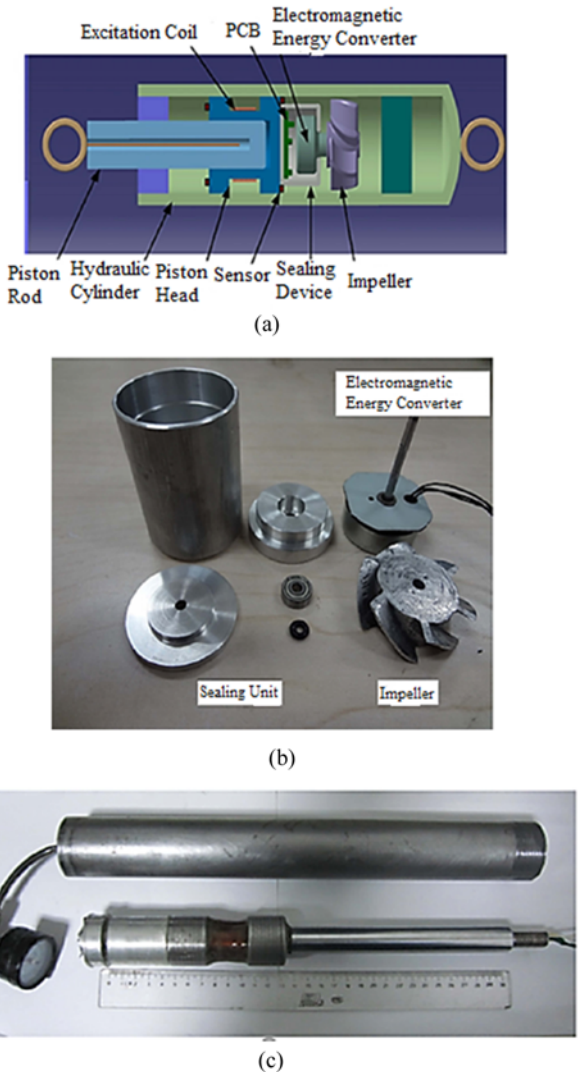


Fig. 68. (Color online) (a) Schematic of the proposed MR damper, (b) assembly parts, and (c) prototype of the proposed damper (Yu *et al.*, 2014).

7. Conclusion

MR damper is a smart semi-active device, which has some certain advantages over passive and active devices like continuous controllability, comparatively light weight,

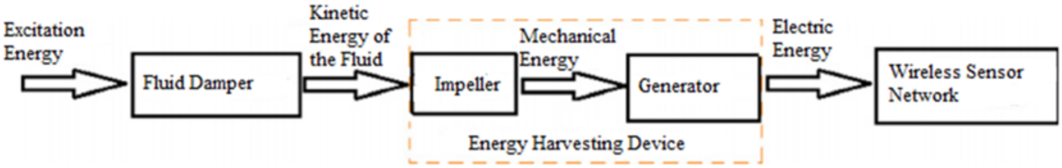


Fig. 67. (Color online) Energy generation system from fluid damper (Wang *et al.*, 2012).

and low power consumption. MR dampers basic design and construction along with their various types configuration are discussed in the paper to understand their versatile applicability in a wide area as mentioned in the literature. The way of characterizing the non-linear complex behavior of MR damper is accomplished with the support of some famous MR damper mathematical modelings and all these are summarized here. To cope up with altered applications, design modification, optimization, and advancement are specified in this review. Self-energy generation is crying need of present era and challenge of contemporary technology. In this regard, self- powered *i.e.* energy harvesting capability of MR damper from the wasted mechanical energy are conferred here with their proper modeling. Overall, various MR dampers' design, fabrication and nifty application, damper's design optimization, advancement, and latest self-powered technology are appraised in this paper.

Acknowledgement

The authors would like to thank the Faculty of Engineering, International Islamic University Malaysia for giving the chance of using the basic structural laboratory.

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