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Magnetorheological fluid: Basic principle, application, and trends

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Application;
Vibration control.

Abstract

Magnetorheological Fluids (MRF) are used in a wide range of controlled systems. MRFs have found widespread commercial use, particularly in vibration control. MRF is a type of intelligent fluid found in oil carriers. A magnetic field raises a fluid's apparent viscosity until it becomes a viscoelastic solid. A variable magnetic field intensity controls the fluid's yield stress when it is active. Control-based applications can be created by using an electromagnet to control the fluid's ability to transmit force. In MRF, more nuanced ferrofluid particles are used. Brownian motion cannot suspend MR fluid particles in the carrier fluid due to their thickness. Brownian motion suspends nano-sized ferrofluid iron particles, which reduce sedimentation and increases the performance of the MRF. Dampers, brakes, bearings, pneumatic artificial muscles, optics finishing, fluid clutches, and aerospace all use MRF technology. The characteristics, applications, modes, and models of MRF are investigated in this paper. Understanding yielding, flow, and viscoelastic behavior in the presence of shearing fluxes are critical. Various applications of MRF in various domain of engineering is discussed with valid examples. In a concise manner, the author discusses the utility of MRF for active and semi-active vibration control systems.

1. Introduction

In Magnetorheological Fluid (MRF), the identical rheological particle properties of the particles in the carrier fluid are applied with a magnetic field to alter its properties. MR fluid is an innovative fluid in a carrier fluid, typically oil and water, where a magnetic field converts a liquid into a viscoelastic solid. The magnetic field intensity is significantly used to alter the fluid's yield stress when active. Its capacity to transmit force-controlled with an electromagnet opens up a wide range of control-based applications, and its strength can be effectively controlled during transmission force [1]. MR fluid, when a magnetic field is applied, we get the apparent viscosity, increasing right from liquid to solid.

This article discusses the basic principles of how the MR fluid works. The magnetic particles, typically micrometers, nanometer scalesplurs, or ellipsoids suspended within the carrier oil, are distributed randomly in suspension under normal conditions/circumstances [2]. Spheres of the size of these nanoparticles are suspended within the carrier oil and distributed randomly in the viscous carrier fluid. Furthermore, under normal circumstances, the random orientation of these magnetic particles is pretty standard in any conducting and non-conducting oil [1-3]. Nevertheless, when the field is on means, i.e., the magnetic field is being applied, this microscopic particle ranging from 0.1 to 1 micrometer gets aligned along the magnetic flux line.

Furthermore, a chain of particles restricts the fluid's movement when the fluid is between the two poles, separated between 0.5-2 nm. Moreover, they are aligned perpendicular to the direction of magnetic flux, which is why there is an effective increase in the viscosity of the part [4].

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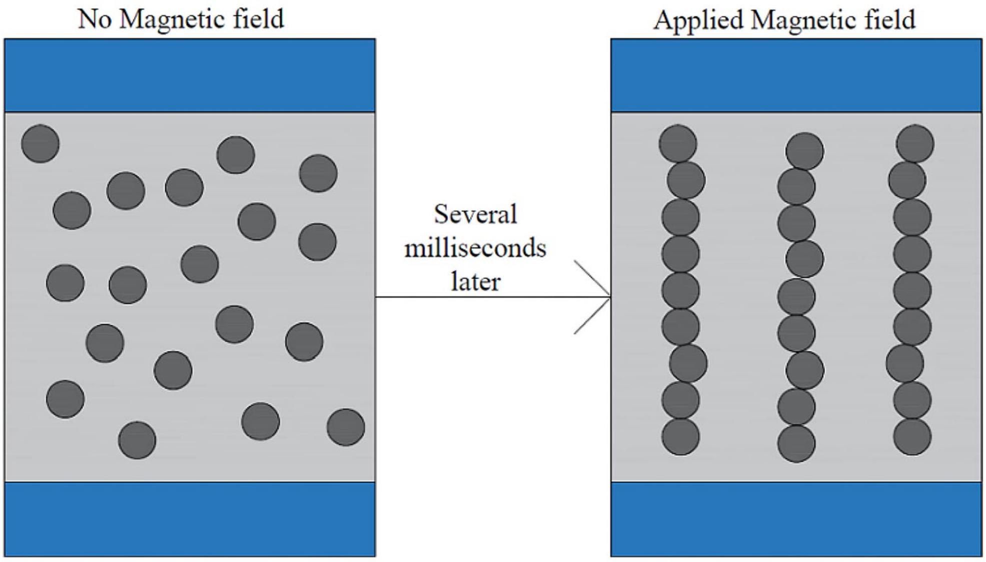

Figure 1. Magneto-rheological fluid.

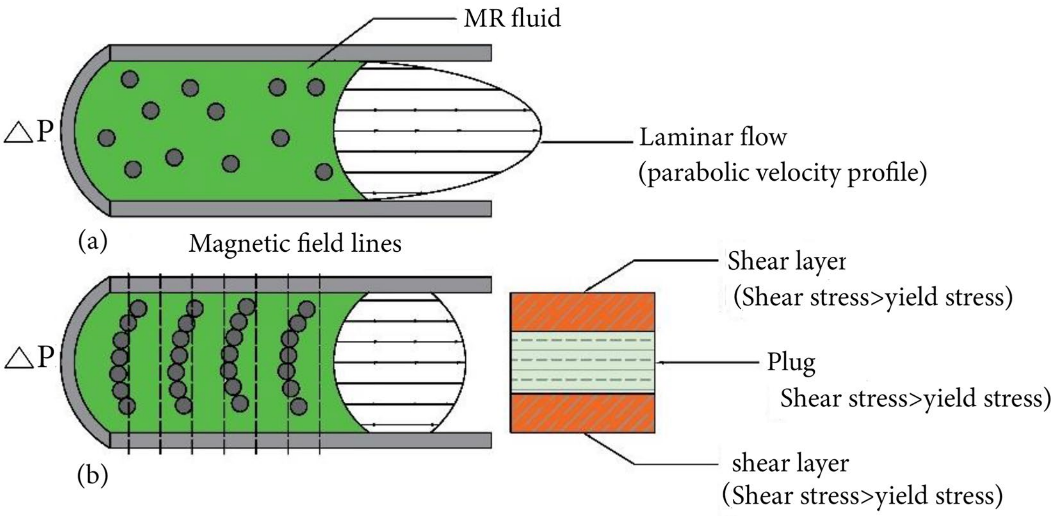

Figure 2. Laminar flow pattern with a pressure change in MR fluid.

Moreover, the states are anisotropic when the mechanical property of the fluid is in an active situation. Thus, in designing the MR device, it is crucial to ensure that these flux lines are there, and they must be perpendicular to the direction motion which is to be restricted. The applied magnetic flux should be perpendicular to that direction only.

Figure 1 shows the carrier oil and the magnetic iron particles that are randomly oriented, and need to be arranged on the column-wise side, not on the row side [1,2]. The particles forming the chains in the direction of flux lines are the direction of the magnetic flux perpendicular to these lines. Moreover, they are just forming the entire column-wise structure, so we can see when it is on from the liquid to the solid phase, then we have a streamlined structure. Furthermore, when it is not on, we have the randomly oriented fluidic particles, or even we can observe them in Figure 1.

When no field is applied, the random orientation between the carrier fluid and the fluid particles is off state [3]. When an electric field is applied, the orientation changes because we now want the resistance in this direction, the vertical column direction. As in Figure 2, we can see what the pressure change is when it is in these magnetic fields. We can also see MRF exhibiting a laminar flow pattern. We can clearly observe that parabolic velocity profiles are there along with that when it is off Figure 2(a), but it is the magnetic field lines along with it when it is "on" Figure 2(b).

The orientation along with these particles aligned with these parts, and we can say that we have the shearing layer in which the shear stress is more than the yield stress. We can also say that there is a plugin feature in this part where the shearing layer is just on the top and bottom. So, suppose we look at this with the perfect laminar feature. The shear stress dominates in the top and bottom region, i.e., we can classify it as shearing mode [4]. Even when we look at this part, we have the entire feature that the particles and carrier oils form in this shearing mode.

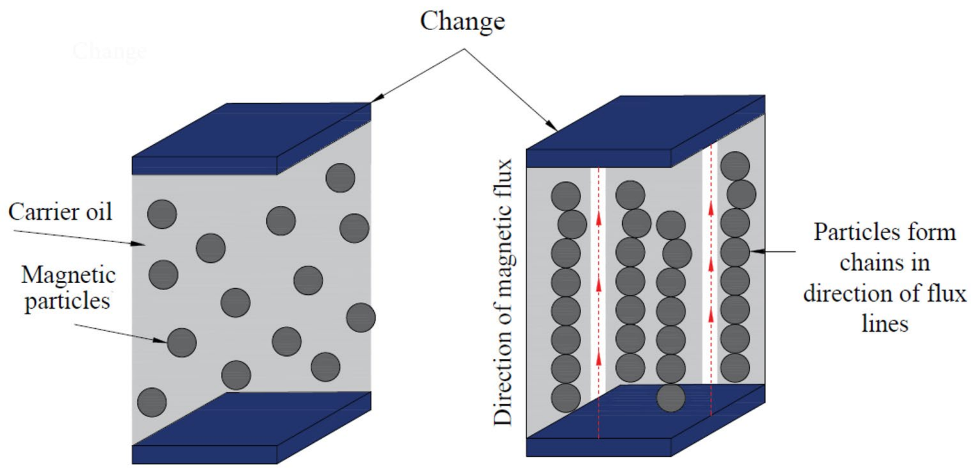

Figure 3. Chain formation in the presence of a magnetic field.

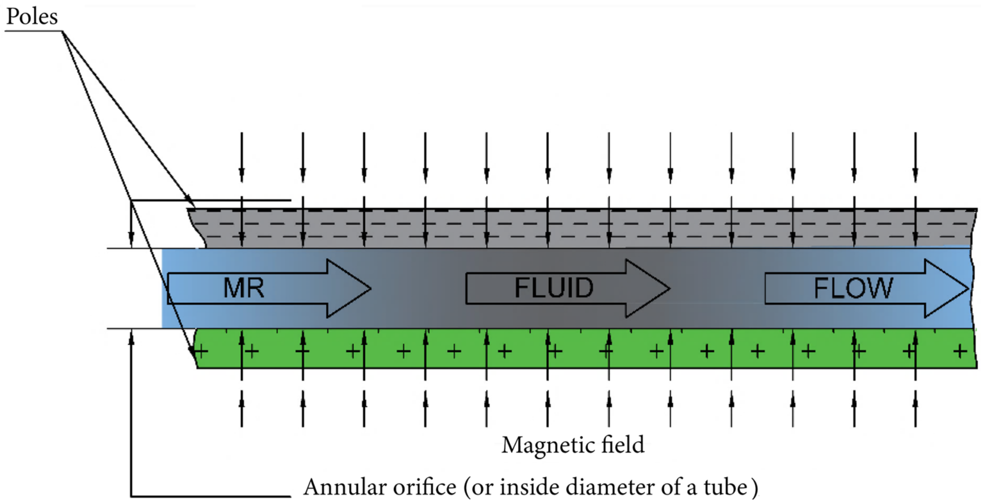

Figure 4. Valve mode.

For clear visualization, we can take the milk (no magnetic field) as in Figure 3, where all the particles are randomly oriented, and water is a carrier fluid. As in Figure 3, the entire milk converts into cheese when the magnetic field is applied. This is one way we can explain the liquid form of the fluidic nature in layman's terms. It is converted into a solid form because all the magnetic particles are aligned and just show the resistance in the direction where they are aligned [2,5]. When we want to see resistance in the column direction, we can put the column feature or the row feature when we want the resistance in the row direction.

In the case of MRF, a magnetic field generates the chain-like arrangement of the suspended particles by simply inducing a magnetic field and exhibiting yield stress, which increases with the applied field strength and can also characterize a pre-yield region. Moreover, the post-yield region can be characterized by viscous properties [3]. In comparing the elastic and viscoelastic features, the pre and post yield regions are an essential factor in studying their behavior. Due to their qualitatively similar behavior of ER fluid and MRF, both fluids are used in damper. A damper, which uses MRF, is an advanced version of conventional dampers where the damping can be controlled due to the controllable MRF governing the damper [4,5].

This article discusses the principles of MRF, operating modes of MR damper, Models governing the working of MRF, and the application of MRF and MR damper in various engineering domains. This article's main objective is to present a clear and basic understanding of MRF and MR damper.

2. MR damper operating modes

A MRF is used in one of the three modes of operation where we see the essential directional features [6]. The first mode is the flow/valve mode, and the second mode is the shear mode. The third mode is the squeeze flow mode, where the MR fluid operates.

When we talk about the flow model shown in Figure 4, in the valve mode, the MRF is made to flow between the static plate by a pressure drop. The magnetic field can control the flow resistance, generally running in the flow direction. Only it is effective, and we can get proper resistance. For

Figure 5. Applications based on valve mode operation. (valve, clutches & shock absorber).

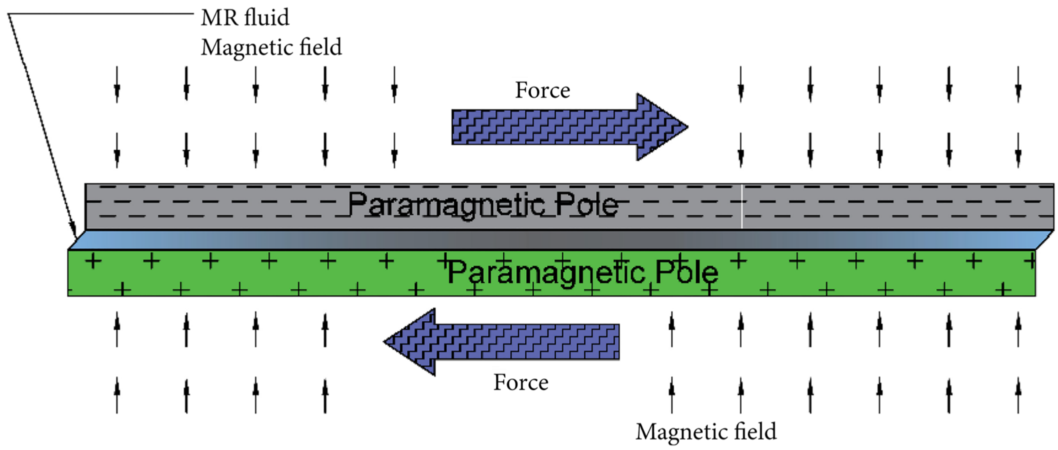

Figure 6. Shear mode.

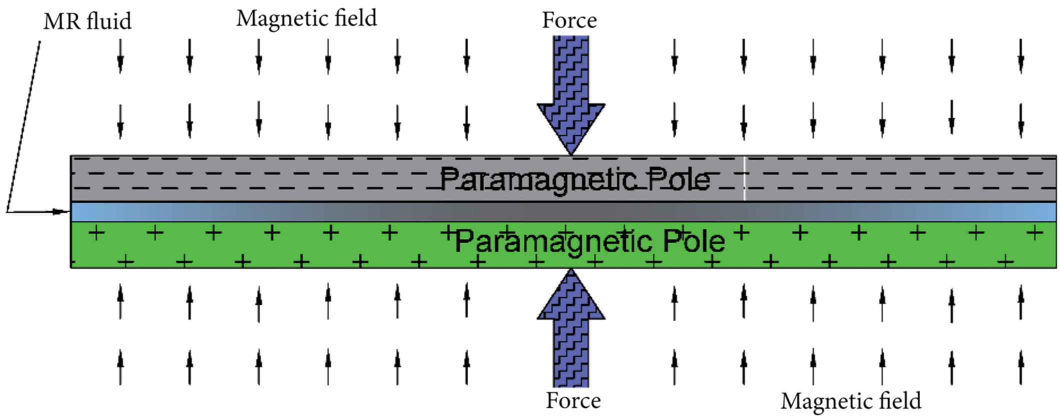

Figure 7. Squeezer mode

example, the flow/valve mode can be observed in servo valve dampers, shock absorbers, and even actuators, as shown in Figure 5.

In the shear mode, the MRF is located between surfaces moving (sliding/rotating) about each other, with the magnetic field flowing perpendicularly to the direction of motion of the shear surface [6], as shown in Figure 6.

The characteristics of the shear stress versus shear strain, we can also say shearing rate because when the shear stresses are present, the shear strain is always present, and the strength of this magnetic field can control it.

As for the last mode, i.e., the squeeze mode, as shown in Figure 7.

The distance between the parallel pole plate changes. When the distance changes, they cause the squeeze action from the magnetic particle [6]. Moreover, in this mode, a relatively higher force can be achieved because of the squeeze action of magnetic particles, and the reaction features are highly reactive. This model is especially suited for damping vibration with low amplitudes and high dynamic forces. We can observe significant forces going up to a few millimeters of the amplitude, and this squeezed part can effectively absorb the energy against that. Because of its fundamental operational features, the squeeze mode has been used in some small-amplitude vibration dampers.

We can see that all three modes can be seen straightway above. When we have a flow/valve mode in Figure 4, it depicts the flow direction and the magnetic field are applied generally to it to achieve the flow features. When we have the shear mode as in Figure 6, they are parallel to the surface

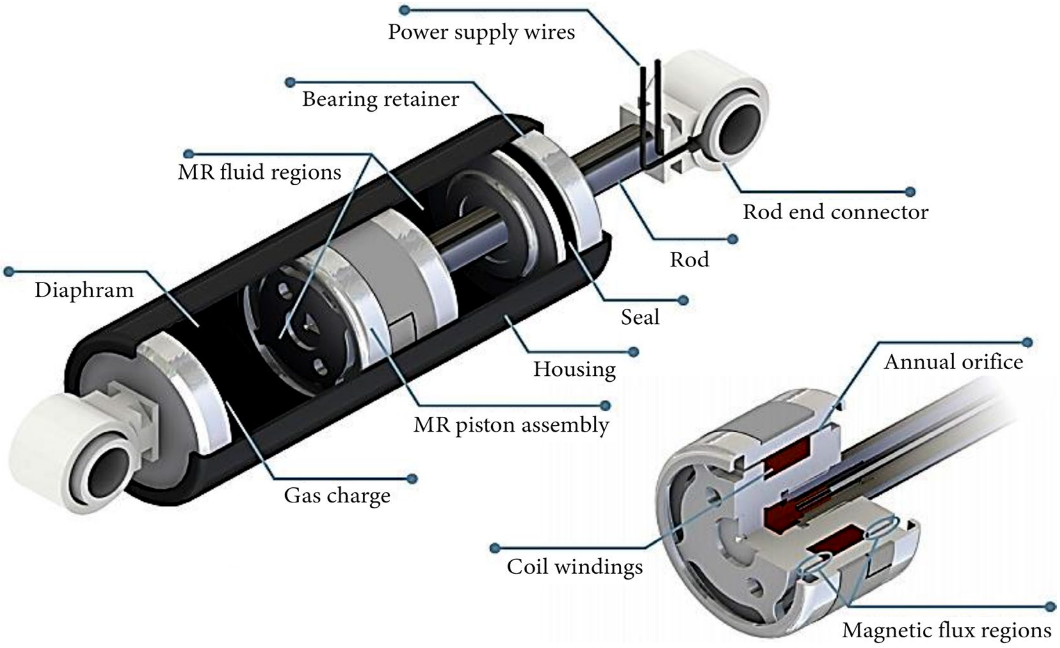

Figure 8. Components of MR damper.

either in the rotational or any part with shear force. Furthermore, the displacement changes when we have the squeeze mode as in Figure 7. Due to this, squeezing features occur at the magnetic particles, resulting in a high force with low amplitude application.

The application of these various modes is numerous. Flow mode can be used in dampers and shock absorbers by controlling the movement to force the fluid through channels across which a magnetic field is applied. This is a smooth point where we want to absorb or dampen the vibration, and this is one of the perfect parts to be applied here. Shear mode is mainly used in clutches and brakes where rotational motion must be controlled. It is a perfect shear motion because it ultimately puts the parallel forces in rotational or sliding actions.

On the other hand, the squeeze flow mode is most suitable for controlling slight millimeter order movement involving large excitation forces. This particular flow mode has a minor investigation because of the high excitation forces with low amplitude features. Overall, between these three modes of operation, MRF can be applied to a wide range of applications according to the service condition and where we want to control the entire vibration or excitation features. So as far as the vibration control problem is concerned, it can act as a damper. So, MR damper has recently become an intensive study area due to its physical features and potential applicability to control damping in the mechanical system. When exposed to a magnetic field, MR fluid changes from a free-flowing linear viscous liquid to semi-solid in milliseconds, with variable yield strength. This feature allows simple, fast interactions between electronic and mechanical systems. MRF dampers are novel semi-active devices that use MRFs to deliver controlled damping forces. These devices avoid many costs and technological issues involved with prior semi-active devices. The linear MR damper design is like an actuator that allows controlling performance characteristics. The resistive force is related to the piston speed and the working gap magnetic field. Large damping force and minimal power consumption characterize MRF dampers. MR dampers are included in many vibration control systems.

Figure 8 represents all the essential components of a complete MR damper. This is the basic arrangement in which we have the piston part, how the piston movement is there and then according to the strength, the strength of the magnetic field for good damping feature. We use the various mathematical models for the damper part when talking about this principle.

3. Mathematical model

Mathematical models represent the mathematical function whose coefficients can be determined using the rheological part. The parametric value is adjusted until the quantitative results are not closely matched with the data. The dynamic response of MRF devices is reproduced in a semi-empirical relationship about the damping part. It uses Numerous parametric models to justify arranging mechanical elements such as spring and viscous dashpots together.

The first model coming under the MR damper is the Bingham model. As in the ER fluid, two features develop (a) Newtonian behavior when under shearing action and (b) non-Newtonian behaviour after the yield limit. There is a clear relationship between shear stress and shear strain rate. So, we have here an explicit Bingham nature itself. We have a similar relationship when applying the magnetic field to these polarized particles. So, the most common behavior of this MRF is described by the Bingham plastic model [7,8].

3.1. Bingham plastic model

An ideal Bingham body behaves as a solid until it reaches the minimum yield stress (τ_y) and when it exceeds itself, they exhibit the linear relation between the stress and the rate of formation of a shearing part. The equation involving the relation of shear stress which is being developed under the action of the magnetic field with the micro particles is given by Eq. (1):

$$\tau = \tau_y.Sgm(\gamma^{\cdot}) + \eta\gamma^{\cdot}\,; \qquad \tau > \tau_y, \tag{1}$$

where, τ is the shear stress; τ_y the shear stress at yield point; $\gamma\gamma^{\cdot}$ the shear strain rate; η *the* plastic viscosityof fluid (newtonian viscosity).

Eq. (1) shows that even if we apply the load up to a specific limit before reaching the yield point, there is no change observed in the solid. However, after exceeding the yield point, it exhibits elastic behavior. $\tau_y.Sgm(\gamma)$ shows a linearity feature, and $\eta\gamma$ shows the shear strain rate, which is absorbed with the viscous plastic feature in the relationship equation given.

Since, it exhibits both viscous and elastic behavior from Eq. (1), we conclude by stating that the Bingham model exhibits visco-elastic features of the material.

In the Bingham model, if we are going below the yield stresses, then indeed, the material behaves viscoelasticity, where we can say that:

$$\tau \propto \gamma, \qquad \tau = G\gamma;\ \tau < \tau_y, \tag{2}$$

where, τ is the shear stress; τ_y the shear stress at yield point; G the complex material modelus; γ the shear strain rate.

G is the complex material modulus and not the shear modulus. However, there is the shear mode. The shear strain rate within the MRF is clearly defined when the relationship of shear strain rate is below the yield stress, and the MR material usually operates within the post-yield continuously shear or the flow regime.

We need to check out the regime and the reason below the yield point or above yield point. If it is below the yield point, it is due to the linearity behavior shown in Eq. (2), and if it is below the yield point, it is due to Eq. (1).

Figure 9 represents the basic Bingham model, which is given in the paper by Spencer et al. [8]. Whenever an exciting force F is applied, we have C_o part, which is the minimum viscous part showing the plastic viscosity there itself, and afterward, a transparent portion of yield point showing the elastic feature in which we can say that $\tau_y.Sgm(\gamma)$, the yield and shear stress rates vary linearly [8].

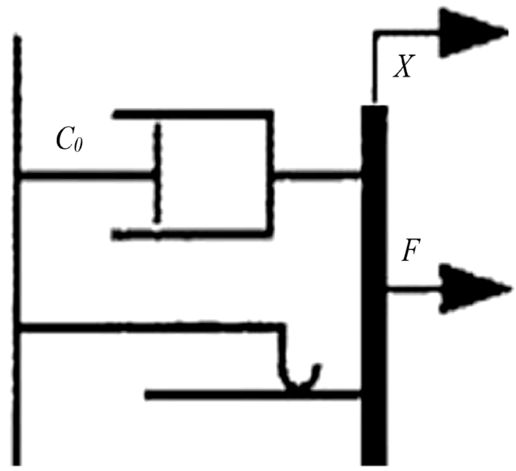

Figure 9. Bingham model [8].

We can also put the mechanical analog of such behavior with Columb friction parallel to the viscous dashpot. So, in this model, while just talking about the columb friction features in that, the force F generated by the MR damper is given by Eq. (3):

$$F = f_c.sgm(x^{\cdot}) + C_0(x^{\cdot\cdot}), \tag{3}$$

where, $x^{\cdot}$ is the velocity attributed to the excitation; C_0 the damping co efficient; f_c the frictional force related to the fluid' s viscosity and field dependent yield stress.

We have here two things together, i.e., the damping, which is absolutely the function of the fluid viscosity, and the frictional forces, which depend on the yield stress along with this f_c which is the frictional force varying with the sinusoidal features sinω or sin $x^{\cdot}$.

When we want to represent the fundamental characteristic of these MRFs, the Bingham model, which is very close to that is accounted for its electro or MRF behavior beyond the yield point, which means when fully developed fluid flow is there, or the shear stresses there are sufficiently high then only we can just go for the actual fluid behavior assuming that the fluid remains rigid in the pre yield region.

Figure 10 represents the visco-plastic model of MR fluid. As we can see from Figure 10, it is clearly shown right from "0" up to "$\boldsymbol{\tau_c}$". The vicious part is dominating and not exhibiting any flow. The energy being there is either dissipated or absorbed at this point. Beyond yield, the linear region or the elastic feature starts exhibiting. So, the viscoelastic model of the MR fluid clearly shows that if we have the Bingham models, it is mandatory to show this part first and go straight till linear propagation is observed. Moreover, if we use the Newtonian fluid model, which starts right from "0" and propagates linearly, showing a solution between shear stress and shear strain part.

The experimental feature with flow and velocity shows how the damping is featured in Figure 10. The green line clearly shows the variation in force concerning velocity.

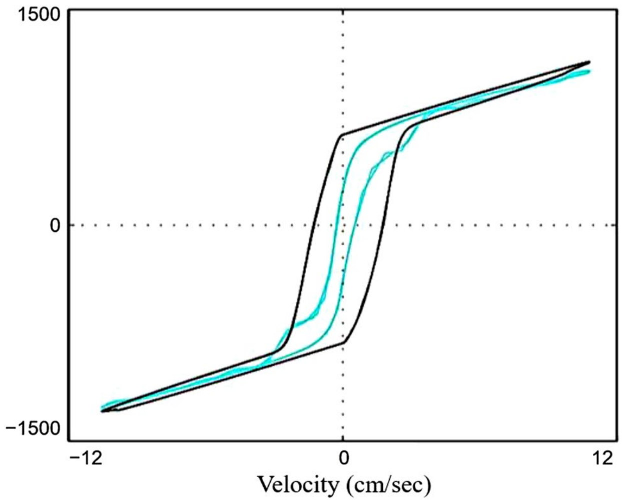

Figure 10. Comparison of force-velocity characteristics for the Bingham model, predicted and experimental model [8].

Table 1. Typical MR fluid properties [7].

Properties	Typical value
Maximum yield strength τ_y	50-100 kPa
Maximum magnetic field η	250 kA/m
Plastic viscosity (Pa-s)	0.1-1
Operating Temperature	-40°C - 150°C
Density (g/cm^3)	3-4
Contaminants	Unaffected by moist impurities
Response time	<milliseconds
η/τ_y	10^{-10} - 10^{-1} s/Pa
Maximum energy dissipation	0.1 J/cm^3
Power supply	2-2.5 V @ 1-2 A

For MR fluid, there is various property documented by Carlson et al. in 1995 [7] as presented in Table 1. We have the typical MR fluid where minimum yield strength up to 100 kPa and maximum magnetic field up to 250 kA-m are observed. The plastic viscosity, the fundamental property before the yield limit, is 0.121Pa.s. It can be operated from temperature -40°C to 150°C. The response time is always less than milliseconds. This is the main characteristic of the MR fluid system and can immediately respond when excitation force is activated. The density is 3-4 g/cm^3 and the relation between plastic viscosity and our yield limit is 10^{-10} to 10^{-11} s/Pa. Other properties include the power supply of 50W, which results in maximum energy density. Bingham model is the first model which can clearly show the fundamental characteristic of MRF, which can be used in MRF for vibration control.

3.2. Bouc-Wen model

A model with a more defined part is the Bouc-Wen model presented by Spencer et al. [8], shown in Figure 11. In this model, we can say only the characterized behavior of this MR fluid damper. So, again we need to produce the hysteresis system's response to the random excitation. So, we can get straight away, which we can see that the force

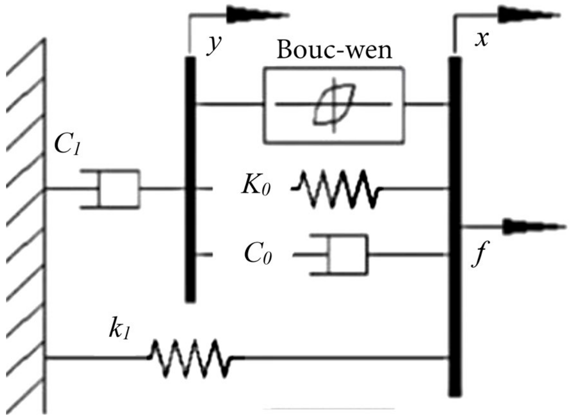

Figure 11. Bouc-Wen model [8].

generated by the device can be represented as shown in Figure 11.

Here, we have the same as the Bingham model, the spring feature, and the damper feature. However, here we are saying that the displacement is "y" and the entire total damper movement is "x" when the external force is being applied, there are three primary devices that are being acted together according to the Bouc-Wen model, i.e., C, K and this device which is all acting together. So, we are just trying to consider these three features or putting the response from the hysteresis system from the random excitations.

Equations describing the Bouc-Wen algorithm for the MR damper behavior can be written as:

$$f = C_1\dot{y} + k_1(x_d - x_o), \tag{4}$$

$$\dot{z} = \gamma \left|\dot{x_d} - \dot{y}\right| z \left|z\right|^{n-1} - \beta x \left(\dot{x_d} - \dot{y}\right) \left|z\right|^n \pm \mathrm{A}\left(\dot{x_d} - \dot{y}\right), \tag{5}$$

$$\dot{y} = \frac{1}{C_o + C_1}\left\{\propto z + C_o\dot{x_d} + K_o(x_d - y)\right\}, \tag{6}$$

where, the primary displacement variables describe f, x_d, and y along with an evolutionary variable z that considers the history dependency. Viscous damping parameters C_o and C_1 as well as the parameter $\propto$ depending on the field variable (voltage/ampere). Parameter β and x_o are constants.

$C_1\dot{y}$ means the real characters of the damper at that time, which is related to all the damping parameters. So, C_o is the first damping and C_1 is the damping occurring outside related to displacement y.

We have the damping force from C_1 as well as $C_1\dot{y}$ plus the restoring force, which is due to the relation with x_d i.e., whatever the variable feature is there in the displacement part and x_o which is the initial part. So, the difference between the damping and the initial part is just giving into K_1. Moreover, the stiffness feature there gives the restoring force.

For the evolutionary variable, we account for whatever the previous dependency feature is there i.e., $\dot{z}$ as given in

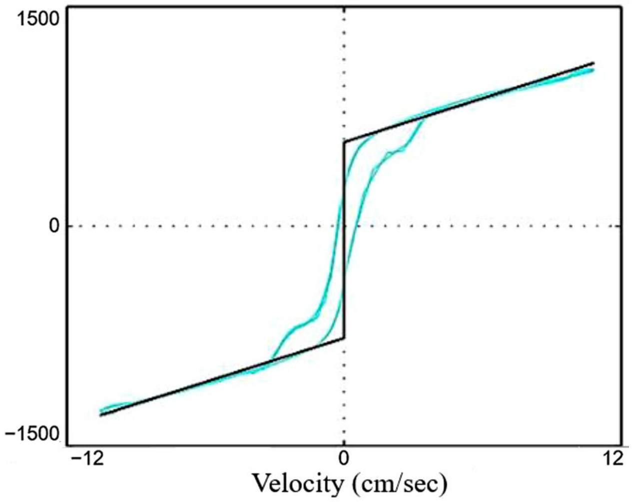

Figure 12. Comparison of force-velocity characteristics for the Bingham model, predicted and experimental model [8].

Eq. (5). When we are just trying to compute these coefficients β and x_o, we are applying here, which is the constraint part, and we are trying to put the boundary conditions.

So, from $\beta x \left(\dot{x}_d - \dot{y}\right) |z|^n$ we can straightaway get these two coefficients according to what the application means, what the boundary conditions are there and what we see the operating features are there all together along with $\dot{y}$ which is there initially as given in Eq. (6).

Referring to Eq. (6) $\dot{y}$ is known as the velocity components where: C_o and C_1 are the viscous damping parameters; $\propto z; \propto$ the field variable depending on the applied voltage into z; and z is the evolutionary variable depending on how the dependency features are there in the previous part of $C_o \dot{x}_d$ because C_o is just moving along with $\dot{x}_d$. So, we have the viscous force with that, plus $K_o(x_d - y)$ since the displacement considered is y. So, the Eqs. (4)-(6), which are based on the Bouc-Wen, simply shows the relation of all these parameters when the entire fluid damper model is behaving under the excitation force "f" and when we are trying to make the predicted part between experimental and theoretical part in Bingham model.

When the whole feature is present, the hysteresis loop is represented by Figure 12 in a way that is easy to understand. When the green part of the experimental component is present, as shown in the image, the nonlinearity may be seen very clearly [8].

The original Constitutive Models of MRF, proposed by Bingham and Bouc-Wen, have been modified and are presented in a tabular format for better interpretation in Table 2.

4. Application

Semi-active vibration control devices are MR dampers, and it has numerous applications in the automotive, defense, and medical fields. On the other hand, the MR damper system's uses are limited to shock absorbers in autos. They are being utilized in military research in defense, medical applications such as prosthetic limbs, and enormous constructions that can be thoroughly safeguarded from catastrophic events like earthquakes.

4.1. MRF in defence

The activity of all weapon parts and mounting during launch is covered by gun mechanical systems. Gun mechanics examines dynamic behaviour, system stress, and component stress [11]. Researchers are now conducting studies on incorporating MR damper in construction of a run recoil system couple with adaptive H-SAFC algorithm. The evaluation, depicted in Figure 13 is carried out using simulation and experimentation, as well as time-domain analysis of performance metrics such as acceleration, forces and jerking of the gun recoil system [12].

Researchers are now conducting studies on the material to construct a smart bulletproof vest comprising layers of MRF. This vest alters its mechanical properties when passing it through a magnetic field in the blink of an eye. The vest is light and flexible when there is no magnetic field, but it may be stiffened by just flipping a switch. Defense research agencies are developing armor suits made of MRFs to withstand the impact of explosives by preventing shrapnel from breaching the armor's surface. California United States Army is experimenting with magnetic resonance dampers in heavy vehicles like the HMMWV Hummer. It will still take more research and development in this arena to ensure that MRF vests stop bullets in the conflict soon [13].

4.2. MR dampers in mechanical engineering

MRF dampers are becoming more and more popular in semi-active vehicle suspension applications due to their mechanical elegance, significant dynamic range, power efficiency, tremendous force capacity, and reliability. By tweaking the magnetic field strength on an MR damper, a multi-DOF vehicle system's MR damper can provide both driving experience and cruising stability. MR dampers are simple, reliable, durable, and lack moving parts. MR dampers reduce vertical and steering movement [14]. For 2-DOF car seat suspension presented in Figure 14, an innovative adaptable fuzzy control unit connected with the H-infinity approach was developed by Phu et al. [15]. When compared to the performance of a fuzzy controller, the vibration control performance achieved by employing an adaptive controller was shown to be much superior. The dynamic performance of a three-wheeled vehicle with a MR damper has been evaluated and presented. Successfully investigated parameters of MRFs are used to quantify the dynamic force of the MR damper using a quasi-flow-mode in the MR damper model. Three-wheeler ride comfort and stability have been studied utilising an MR damper model with

Table 2. Constitutive models of MR fluids [9,10].

Constitutive model	Description	Equation	Applicability	Limitations
Bingham plastic model	Describes MR fluids as having a yield stress below which they do not flow and exhibit linear behavior	$\tau_y = .Sgm(\gamma) + \eta\gamma$	Suitable for MR fluids with distinct yield behavior	Does not capture shear-thinning or shear-thickening behavior
Bouc-Wen model	Employs a nonlinear differential equation to describe hysteresis behavior in MR fluids, capturing rate-dependent and asymmetric responses	Differential equation incorporating nonlinear stiffness and damping terms.	Suitable for modeling hysteresis and rate-dependent behavior in MR fluids	Requires knowledge of system-specific
Herschel-Bulkley model	Extends the Bingham model to include shear-thinning or shear-thickening behavior	$\tau = \tau_y + K\gamma^n$	Applicable to MR fluids exhibiting non-Newtonian behavior	May require empirical fitting parameters
Carreau-Yasuda model	Generalized rheological model for viscoelastic fluids, transitioning to Newtonian behavior at high rates	$\mu = \mu_0 + (\mu - \mu_0)(1 + (\lambda\gamma)^a)^{((n-1)/a)}$	Suitable for MR fluids with shear-thinning behavior	May require fitting parameters and may not accurately capture transient behavior
Modified Bingham model	Extends Bingham model with a smooth transition between solid-like and fluid-like behavior	$\tau = \tau_y + (\tau_\infty - \tau_0) * \tanh(\gamma/\gamma c)$	Suitable for MR fluids with gradual yield stress behavior	May require empirical fitting parameters
Fractional order model	Describes MR fluids using fractional calculus, allowing characterization of non-integer order dynamics	Fractional derivative of stress with respect to strain, where the order of the derivative is a non-integer value	Suitable for capturing complex viscoelastic behavior in MR fluids.	May be computationally intensive and require specialized numerical techniques

PID control by Tharehallimata et al. [16].

Apart from application in automobiles, MR damper is also being used in stabilizing the aircraft. Yoon et al. [17] developed a new control logic for landing gear systems that uses MR dampers and focuses on the absorption of variable mechanical energy by the landing gear depending on landing conditions to reduce impact load by controlling the MR effect until the landing gear's initial compression stroke.

Aircraft landing gears as depicted in Figure 15, serves to limit the amount of force imparted to the airplane body during landing. Because of their excellent landing efficiency per unit weight, landing gears oriented towards passive oleo-pneumatic are commonly utilized [18]. However, under all design parameters, this sort of passive landing gear cannot achieve ideal performance. To overcome the limitations of passive landing gears, MR dampers with two compartments have been proposed for use in aviation landing gear systems. A normal skyhook controller is used for controlling the MR landing-gear systems. Although the landing efficiency of a skyhook controller is superior to that of a conventional landing gear system, the improved skyhook controller limits the performance of the aircraft's velocity. To overcome this limitation as depicted in Figure 16, a hybrid control system comprised of a force control and a skyhook control system has been proposed and implemented in MR landing-gear systems [19].

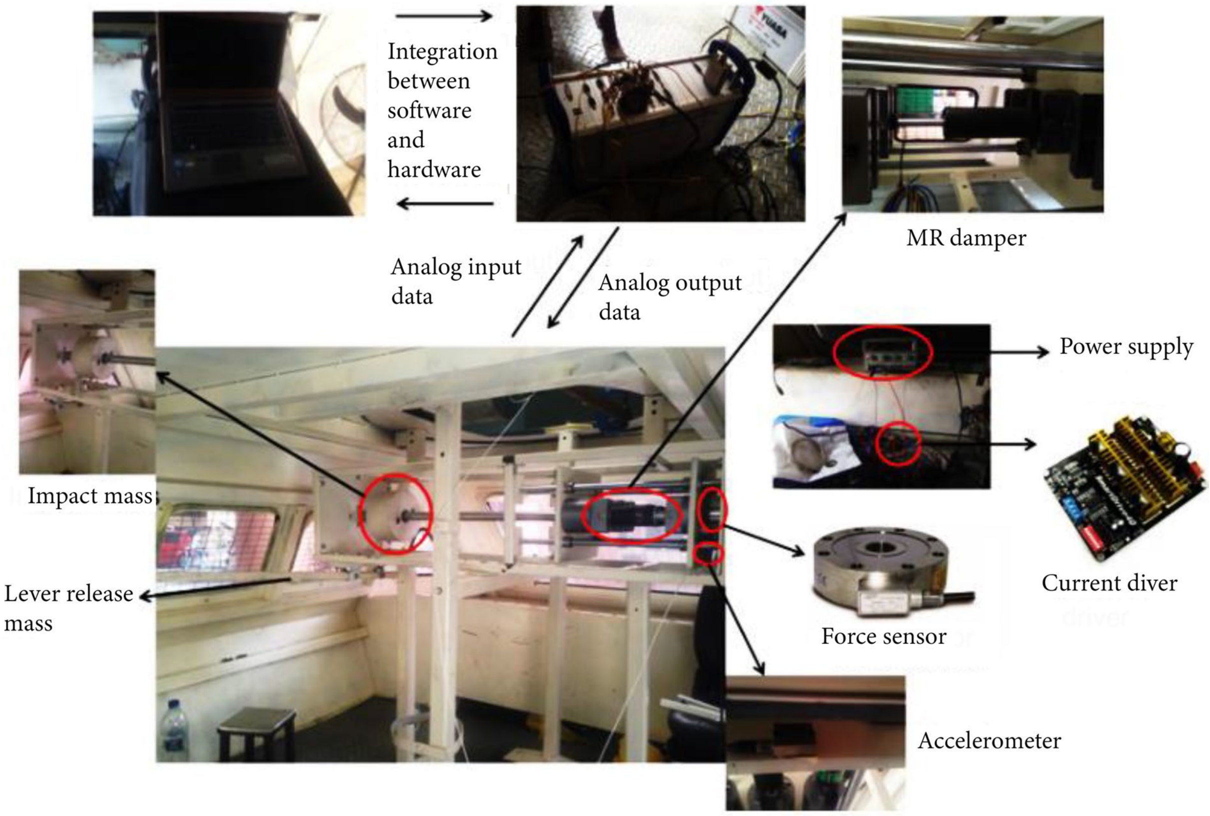

Figure 13. MR damper for reducing gun recoil [12].

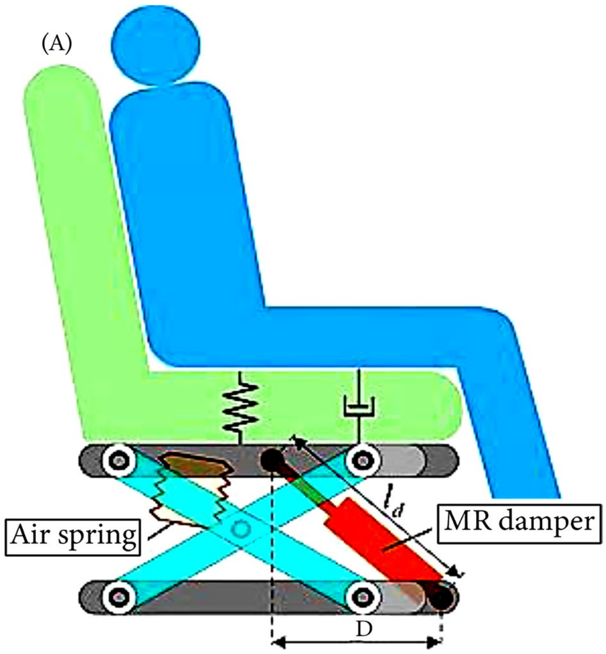

Figure 14. Seat system with MR damper [15].

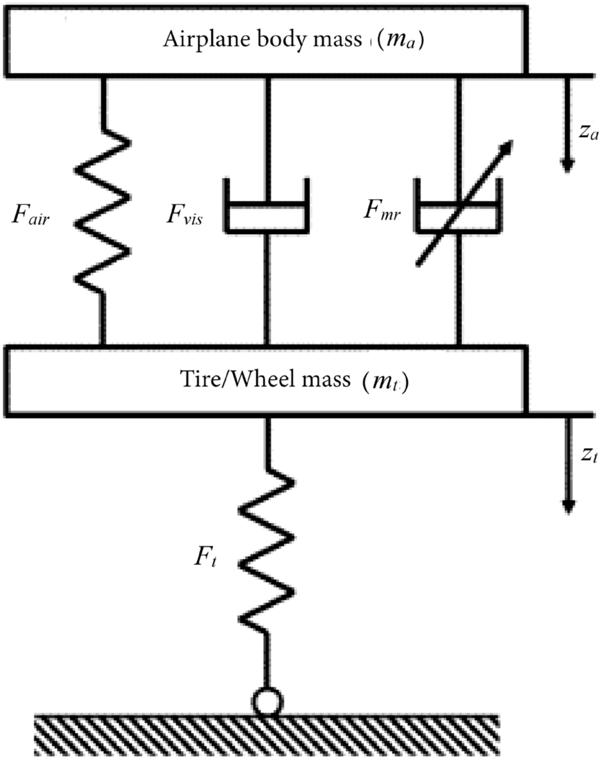

Figure 15. MR damper in Landing gear [16].

Recently, magnetorheological brakes have been employed in haptic devices for passive force/torque feedback due to their safety and low power consumption. A study by Chen et al. [20] combined the benefits of linear and rotary MR brakes to create a new rotary MR brake. The brake converts shaft rotation into piston reciprocation, enhancing Torque-to-Volume Ratio (TVR) in the MR brake. Additionally, psychophysical investigations assessed the subjective perception of output torque from the two actuators. Research indicates that increasing torque feedback accuracy enhances haptic interactions and transparency.

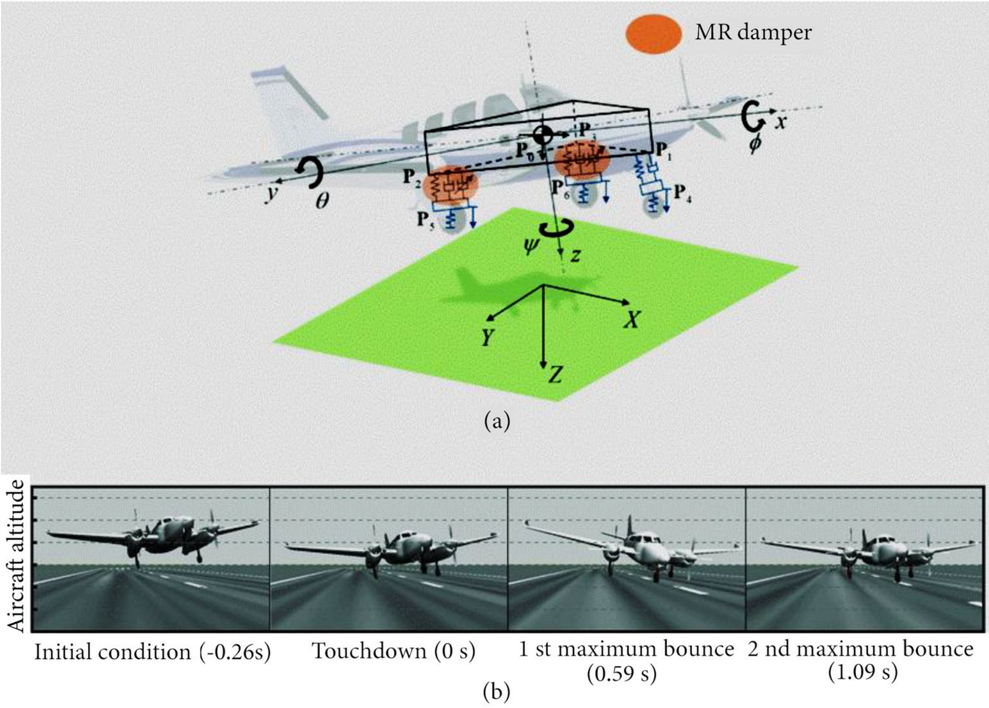

Figure 16. (a) Aircraft with MR damper and (b) landing simulation of aircraft with skyhook system [19].

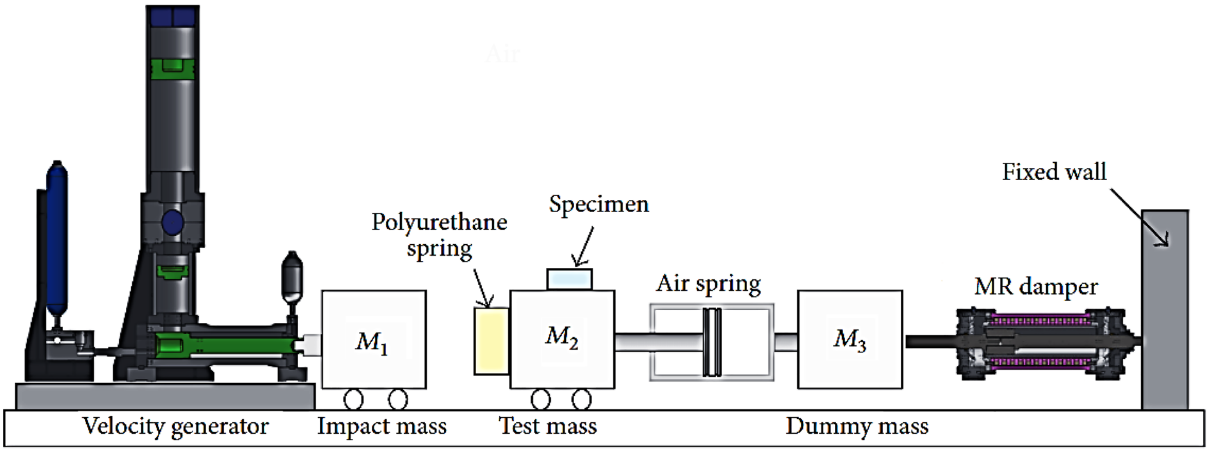

Figure 17. Mechanical model for shock-wave profile test [24].

MRFs take a new approach to polishing and surface finishing. These unique fluids may change from liquid to semi-solid under a magnetic field, allowing precise polishing control. Magnetorheological Finishing (MRF) hardens MR fluid around a polishing tool to form a moldable abrasive head. This approach controls material removal to produce high-quality surface finishes on metals, glass, and delicate optics. Magnetorheological Jet Finishing (MRJF) uses an abrasive MRF jet [21]. A magnetic field controls the jet's direction and shape, enabling accurate material removal for shaping and polishing complicated geometries. MRJF is versatile in surface finishing applications, especially in hard-to-reach locations or sensitive components. A great surface finish with minimum subsurface damage is possible with MR fluids in polishing. The magnetic field may be tailored to polish complicated items with different surface characteristics, making it applicable across sectors [22]. Reusable MRFs reduce waste and environmental effect compared to typical polishing methods. MR technology is potential for surface finishing, especially for high-precision applications and delicate components [21,23].

4.3. MR dampers in railways

Looking upon the various forces acting on a railway boogie, it is possible to construct a shockwave profile by utilising an MR damper as shown in Figure 17. Impact tests need to be carried out in order to evaluate shock survival based on shock loading [24]. This is necessary because shockwaves that are generated by noncontact explosions are known to cause damage to the electric gadgets found in submarines. Oh et al. [25] developed a device for performing impact tests, as well

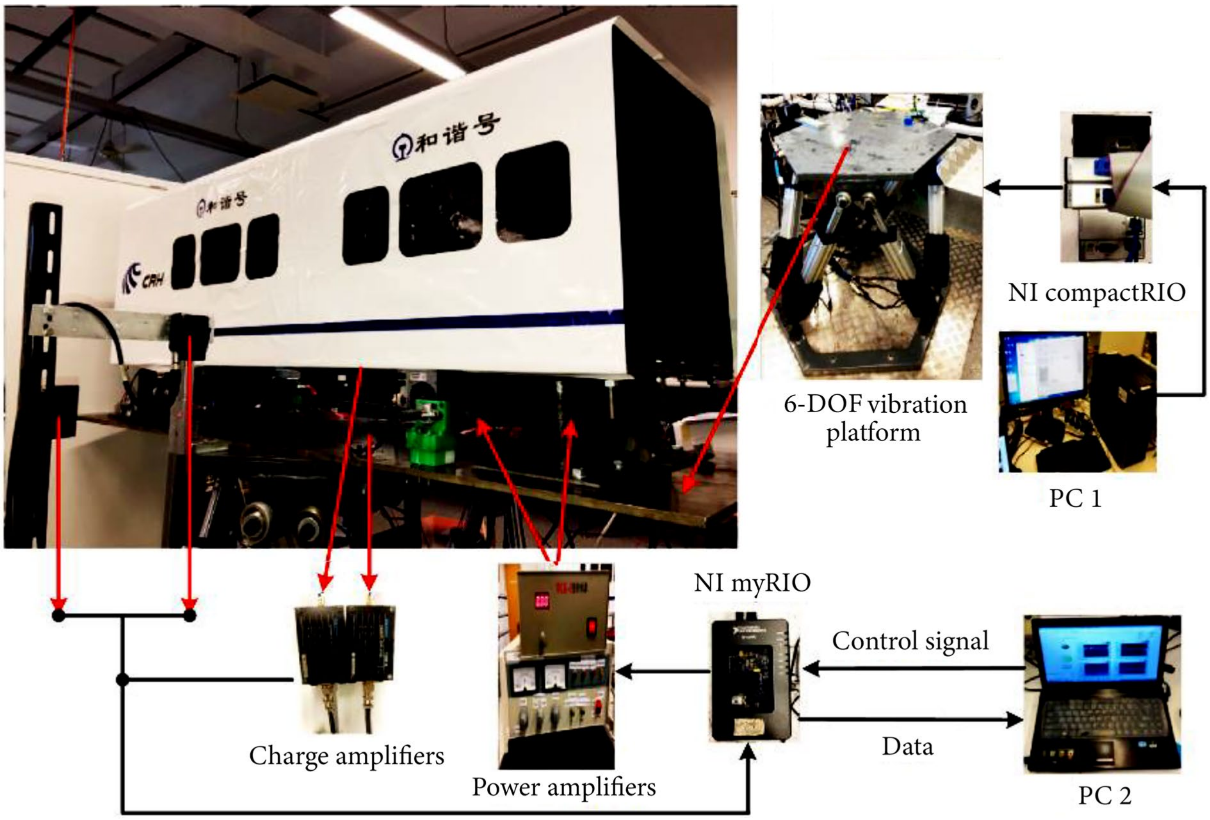

Figure 18. Test setup for MR damper with elastomer in railways [28].

as a field-dependent dual shockwave profile that was later successfully analyzed. The effectiveness of the control was evaluated in the field by Kim et al. [26]. Another form of control approach for the MR dampers used in railway systems was created by a research team. These other control methods include predictive model control and disturbance rejection control [27]. It was determined, on the basis of the control results, that the proposed semi-active suspension solutions had the potential to significantly reduce the vertical vibrations that railway vehicles experience. Jin et al. [28] have just recently developed a novel semi-active suspension that consists of an MR damper in addition to an elastomer for application in railways as depicted in Figure 18.

4.4. MR damper in biomedical

Many research have used MR dampers in prosthetic knees because MRF can adjust stiffness and damping.

Park et al. [29] developed prosthetic leg for above-knee region as shown in Figure 19, that included an MR damper with flat motor. The suggested device consists of a MR damper, flat motor, planetary gear, wearable connector, encoder, gyro sensor, and a hinge. MR dampers develops a resistive force, while the flat motors control knee joint angle during gait. At modest walking speeds, the knee angle matches the ideal angle. At high walking speeds, MR dampers and imprecise knee angle prediction algorithms limit the tracking performance. Pandit et al. [30] designed a

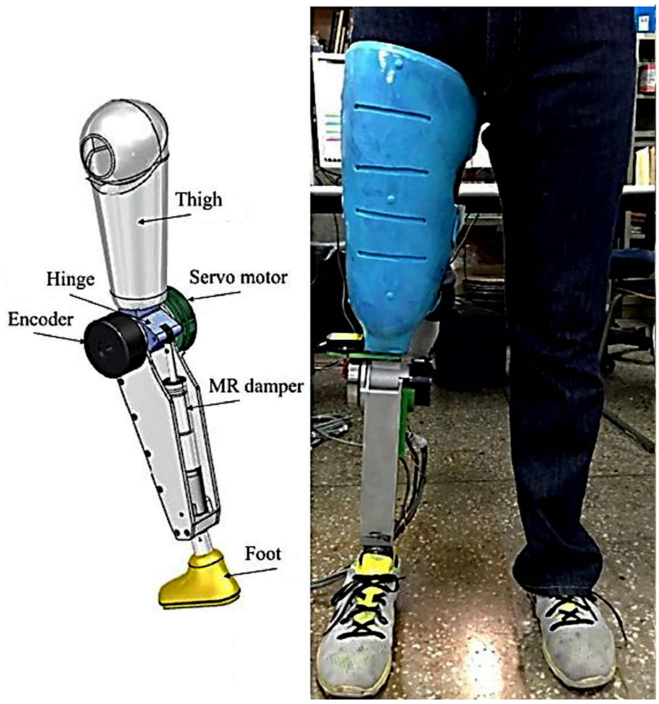

Figure 19. Prosthetic leg with MR damper [29].

prosthetic leg that included a hinged knee joint, an MR damper, and braces to support the limb assembly system. A single-MR-damper-based knee joint mechanism was presented to reduce the cost of the prosthetic limb. It can provide typical gait kinematics for the same price as passive prostheses.

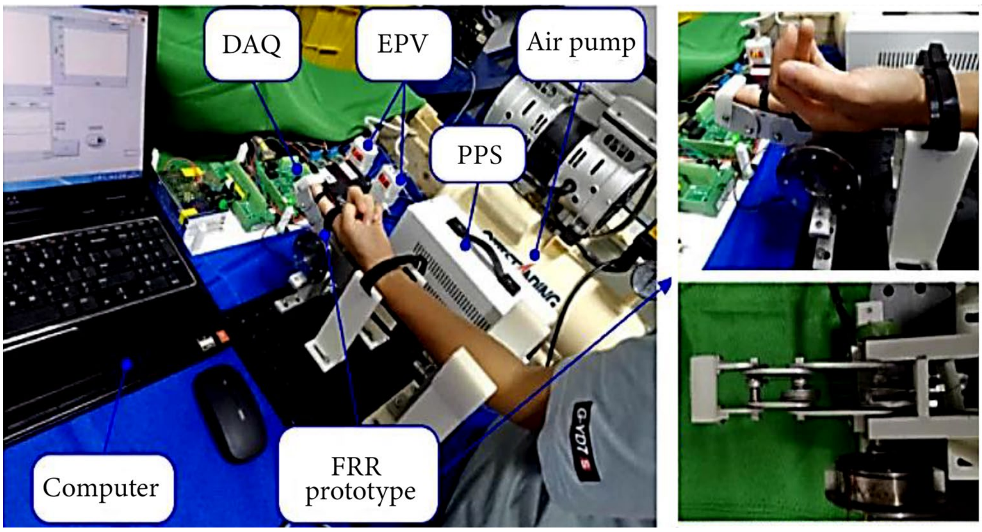

Figure 20. Active-Passive Robotic finger with MR damper [31].

Wang et al. [31] recently devised an active-passive robotic finger for rehabilitation as shown in Figure 20. Passive training was done with an antagonistic pair of pneumatic muscle, while active training was done with an MR damper. The MR damper's current was calibrated to give multiple damping forces to satisfy finger muscle intensity during recovery.

MRFs are currently in trend for its application in haptic devices. The unique property makes them exceptionally well-suited for utilization in haptic master systems, which are devices designed to provide users with a realistic sense of touch within virtual environments [32]. In these systems, MR fluids can create various haptic effects such as force feedback, texture simulation, and friction control. With advantages including fast response times, high force output, and low power consumption, MR fluids stand out from traditional haptic technologies [33]. The applications of MR fluids in haptic master systems span diverse fields, including surgical simulation for training surgeons, assisting in robot-assisted surgeries for enhanced precision, and improving virtual reality experiences through haptic gloves for users to touch and interact with virtual objects, collectively presenting a promising future for revolutionizing human-computer interactions and immersive experiences [34].

4.5. MR damper in civil engineering

Seismic activity damaged RCC structures. Beam-roof-tile and beam-column connections were most damaged. Redesigning the structural system and adding shear walls, classic or dispersion rocking walls, steel or aluminum exoskeletons, and low impact interventions can improve seismic behaviour.

Passive (viscoelastic) and active MR dampers, frictional dampers, adjustable tuned mass dampers, tuned liquid


Figure 21. Diagonal bracing of structure with MR damper [35].

dampers, and base isolation dampers improves structure damping. Recent study shows that MR dampers are best for structural dampening and need less power (allowing operation under battery power). It offers controlled damping force and high force capacity. It's temperature-resistant. Durability and demand make it popular in this field. MR dampers offer non-linear characteristics, strong hysteretic dissipation capacity, and robust performance [35-39]. Chaudhuri et al. [35] performed an investigation as depicted in Figure 21, on frame structure where the structure was

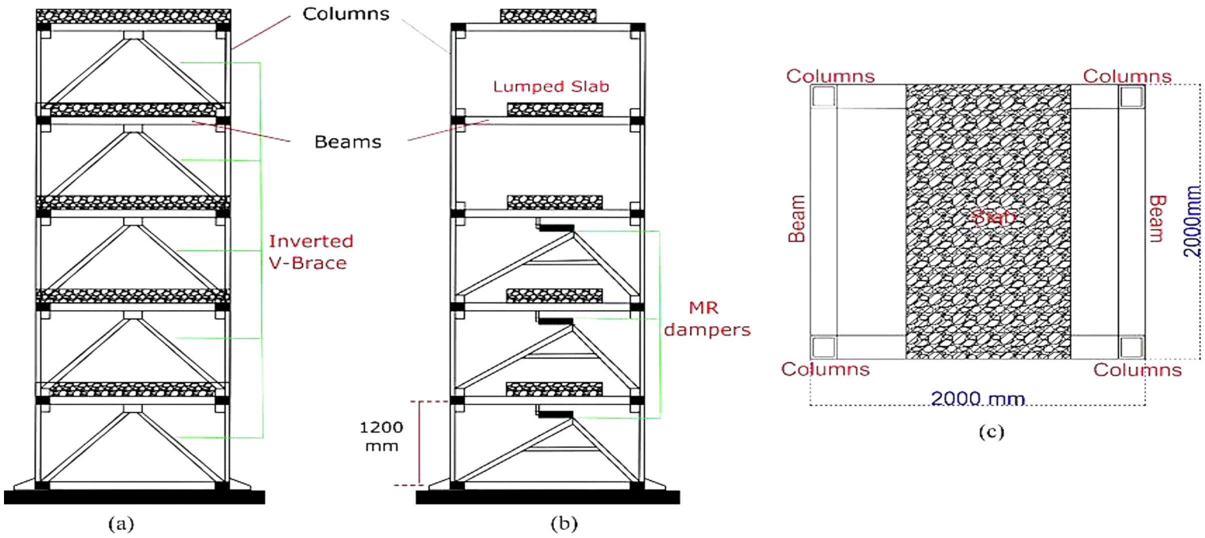

Figure 22. (a) XY elevation; (b) XZ elevation and (c) plan [36].

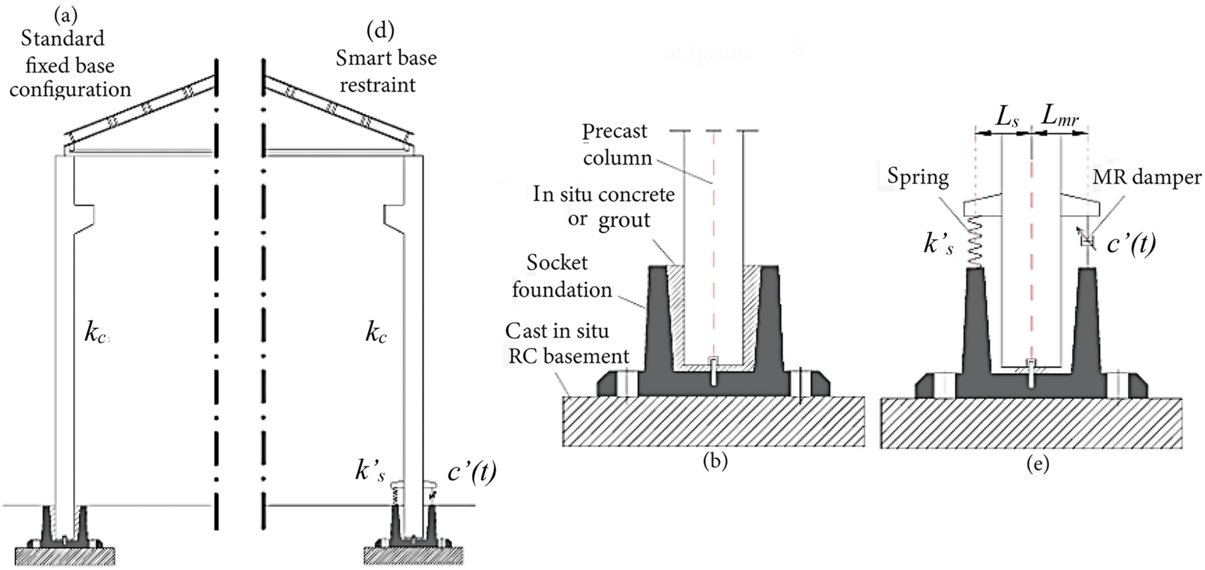

Figure 23. MR damper with precast base [38].

fitted with MR damper diagonally and subjected to cyclic load for studying the vibration reduction of the structure.

Wani et al. [36] investigated a five-story steel frame as in Figure 22, using shake table incorporated with a template matching algorithm for DIC streaming. The MR dampers (ON state and OFF state) change the structural response and evaluate the DIC technique's accuracy and adaptability. Displacement, velocity, acceleration, column base strains and inter-story drift of the floors and were measured and compared with standard transducer data. Rebecchi et al. [37] evaluated the efficiency and stability of a new servo-hydraulic Active Mass Damper (AMD) which can improve seismic performance of a building at various seismic intensities. When subjected to significant ground shaking, the two case-study buildings were supposed to exhibit a soft story mechanism at the first floor, while one was outfitted with the proposed damper. Following that, the two specimens were subjected to the exact loading experiment, which comprised of a highly variable earthquake motion. AMD increases building seismic performance, according to experimental investigations. AMD absorbed 60% of the input energy and reduced peak displacement by 70%.

Caterino et al. [38] investigated an innovative method as depicted in Figure 23, for reducing seismic impacts on pre - cast reinforced concrete structures that uses MR damper as a semi-active control system, with the objective of lowering base bending moment without significantly increasing top displacement response. Using non-linear time history assessments versus natural earthquakes, the usefulness of the suggested technique to reduce seismic vulnerability of existing or new precast structures is emphasized. Waghmare et al. [39] investigated the application of semi-active MR

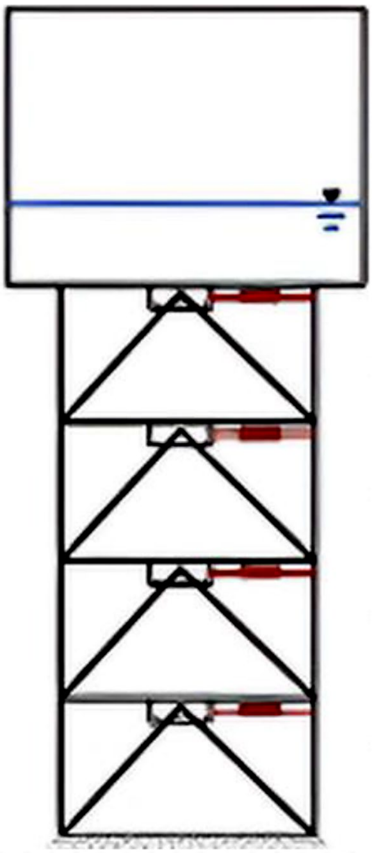

Figure 24. MR damper fitted to elevated water tank [39].

dampers as depicted in Figure 24, to reduce the structural behaviour of elevated liquid storage tanks made of reinforced concrete. The SSC algorithm was proposed in the study as an effective method of controlling the reaction of an RC raised tank by utilising the damper's force-capacity ratio. Control plans and the positioning of the dampers in the staging are used to evaluate the performance of the MR dampers. Both open and closed loop control system are taken into consideration. The suggested simple semi-active control algorithm is a reliable method for RC elevated liquid storage tanks using SAMRD to reduce seismic response.

5. Conclusion

Many researchers are already employing smart fluids in commercial applications. In the future, this trend will be driven by equipment manufacturers who want to increase the value of their products by incorporating smart fluids. Significant changes in automotive, civil, and aerospace engineering are expected in the coming years.

According to the preceding section, smart fluids improve the performance of the devices. Smart fluid dampers can be used in civil engineering to reduce vibrations in buildings. It could be beneficial to use smart fluids in automobiles and aircraft. Many aerospace applications are now receiving special attention as a result of MR fluids. They do not require the high voltages that ER fluids do, so they can be used in different ways. Smart fluids are also widely used in aircraft landing gear. MR fluid-based landing gear is also being researched. Aerospace vehicles can easily use a wire-steering system similar to that of a forklift truck. People driving cars with wire-operated brakes, throttles, and shifters could use MR fluids to maintain tactile feedback. This would be beneficial for two reasons: safety and operator acceptance.

Recent research indicates that significant progress has been made in developing MR materials capable of delivering adequate force and a long stroke. This material must be thoroughly examined by researchers. There is a lot of potential for this breakthrough material to open up many new areas of use in the future, which is very intriguing, but several issues still need to be addressed and investigated. In the formulation of MR fluids, it is critical to achieve the best possible balance of attributes for specific applications or classes of applications.

Although MR fluids have a wide range of applications due to their unique ability to change viscosity, it is difficult to transfer this technology from the lab to the real world.

Cost and Scalability: The presence of rare earth elements in magnetic particles increases the cost of producing MR fluids. For widespread use, cost-effective and scalable production methods are required.
Rheological control: In some applications, the magnetic field response of MR fluids must be fine-tuned. Advanced engineering and characterization are required.
Long-term stability: Extreme temperatures and harsh environments can degrade MR fluids. Maintaining stability and performance over a product's lifetime is difficult.
System integration: Magnets, sensors, and controls help MRFs function. Integrating them seamlessly into existing systems requires extensive design and engineering. The lack of standardized testing procedures and performance criteria for MR fluids makes it difficult to compare products from various manufacturers.

MRFs possess remarkable potential across various industries. Overcoming the challenges of cost, scalability, and integration which is crucial for their successful commercialization. As these hurdles are addressed, we can expect to see MR fluids in more enhanced fields like vibration control, haptics, prosthetics, and industrial automation.

Nomenclature

τ	Shear stress
τ_y	Shear stress at yield point
$\gamma^{\cdot}$	Shear
η	Plastic viscosity of fluid
$\tau_y.Sgm(\gamma)$	Linearity feature

τ_y	Shear stress at yield point
G	Complex material modulus
γ	Shear strain rate
F	Force generated by the damper
$x^{\cdot}$	Velocity attributed to the excitation
C_0	Damping co-efficient
$\sin\omega$ / $\sin x^{\cdot}$	Sinusoidal features
μ	Viscosity of the MRF.
μ_0	Viscosity at zero shear rate, representing the fluid's viscosity at rest
K	Consistency index
kPa	Kilo-Pascal
kA/m	Kilo Amp per meter
f	Viscous force
x	Total damper movement
C_1	Damping occurring outside related to displacement
$\dot{z}$	Evolutionary variable
$\propto$	Field variable depending on the applied voltage in to z
K_1	Stiffness
β	Constant parameter
x_d	Displacement parameter
y	Fixed displacement
x_o	Constant parameter
a	Shape parameter
n	Flow behaviour index
τ_∞	Asymptotic shear stress

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

First author

Shamurailatpam Vivekananda Sharma: Data curation; Analysis; Writing- original draft.

Second author

Hemalatha Gladston: Conceptualization; Methodology; Supervision.

Third author

Daniel Cruze: Writing- reviewing and editing.

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