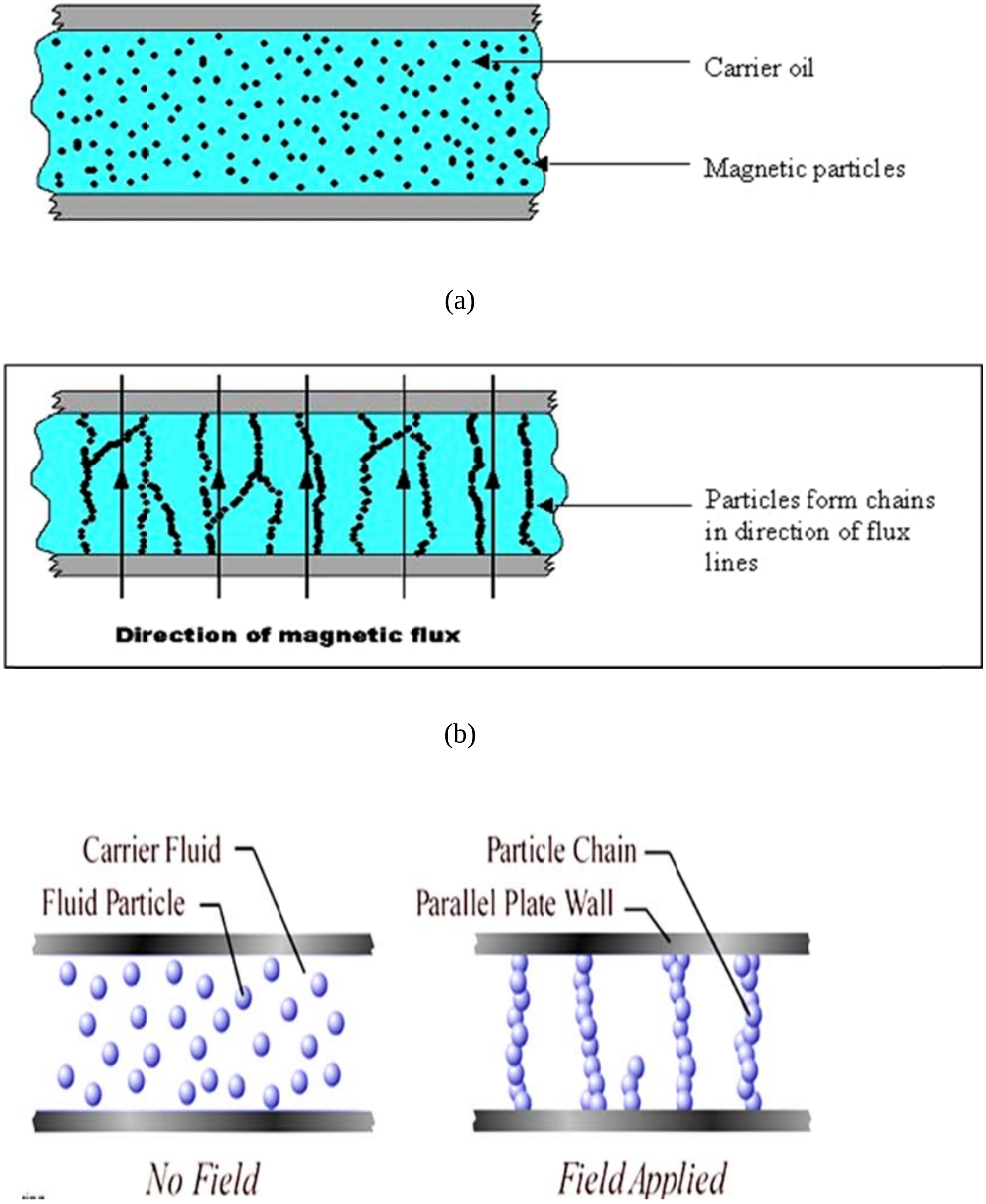
Principles of Active Vibration Control: Magneto-rheological fluids

Introduction:

A **magneto-rheological fluid** (MR fluid) is a type of smart fluid in a carrier fluid, usually a type of oil. When subjected to a magnetic field, the fluid greatly increases its apparent viscosity, to the point of becoming a viscoelastic solid. Importantly, the yield stress of the fluid when in its active ("on") state can be controlled very accurately by varying the magnetic field intensity. The upshot of this is that the fluid's ability to transmit force can be controlled with an electromagnet, which gives rise to its many possible control-based applications. MR fluid is different from a ferro-fluid which has smaller particles. MR fluid particles are primarily on the micrometre-scale and are too dense for Brownian motion to keep them suspended (in the lower density carrier fluid). Ferro-fluid particles are primarily nanoparticles that are suspended by Brownian motion and generally will not settle under normal conditions. As a result, these two fluids have very different applications.

The magnetic particles, which are typically micrometer or nanometer scale spheres or ellipsoids, are suspended within the carrier oil are distributed randomly and in suspension under normal circumstances, as below. When a magnetic field is applied, however, the microscopic particles (usually in the 0.1–10 µm range) align themselves along the lines of magnetic flux, see below. When the fluid is contained between two poles (typically of separation 0.5–2 mm in the majority of devices), the resulting chains of particles restrict the movement of the fluid, perpendicular to the direction of flux, effectively increasing its viscosity. Importantly, mechanical properties of the fluid in its “on” state are anisotropic. Thus in designing a magnetorheological (or MR) device, it is crucial to ensure that the lines of flux are perpendicular to the direction of the motion to be restricted.



(a)

(b)

(c)

Fig. 8.28 Magneto-rheological Fluid

In the case of magnetorheological fluids a magnetic field causes the chain-like arrangement of the suspended particles by inducing a magnetic moment. In addition, MR fluids exhibit a yield stress increasing with the applied field, and both a pre-yield region, characterized by elastic properties, and a post-yield region, characterized by viscous properties (Jolly et al.). Due to their qualitatively similar behaviour phenomenological models of ER and MR fluid devices can mostly be applied to either material.

MODES OF OPERATION

An MR fluid is used in one of three main modes of operation, these being flow mode, shear mode and squeeze-flow mode. These modes involve, respectively, fluid flowing as a result of pressure gradient between two stationary plates; fluid between two plates moving relative to one another; and fluid between two plates moving in the direction perpendicular to their planes. In all cases the magnetic field is perpendicular to the planes of the plates, so as to restrict fluid in the direction parallel to the plates. In the flow mode, MR fluid is made to flow between static plates by a pressure drop, and the flow resistance can be controlled by the magnetic field which runs normal to the flow direction. Examples of the flow mode include servo-valves, dampers, shock absorbers and actuators. In the shear mode, the MR fluid is located between surfaces moving (sliding or rotating) in relation to each other with the magnetic field flowing perpendicularly to the direction of motion of these shear surfaces. The characteristic of shear stress versus shear rate can be controlled by the magnetic field. Examples of the shear mode include clutches, brakes, chucking and locking devices, dampers and structural composites. In the squeeze mode, the distance between the parallel pole plates changes, which causes a squeeze flow. In this mode relatively high forces can be achieved; this mode is especially suitable for the damping of vibrations with low amplitudes (up to a few millimeters) and high dynamic forces. The squeeze mode has been used in some small-amplitude vibration dampers.

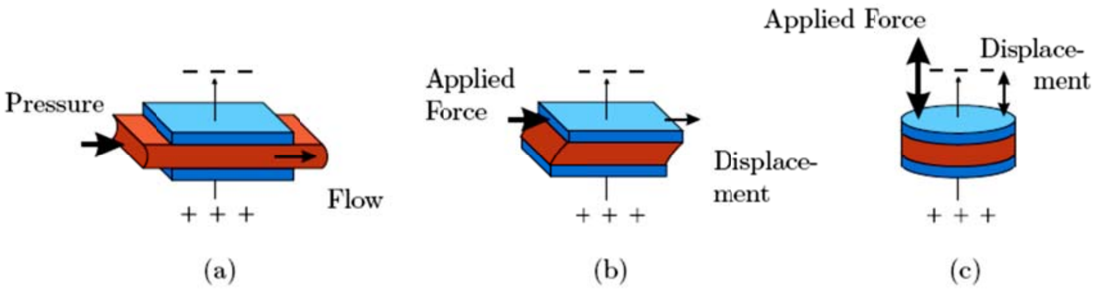
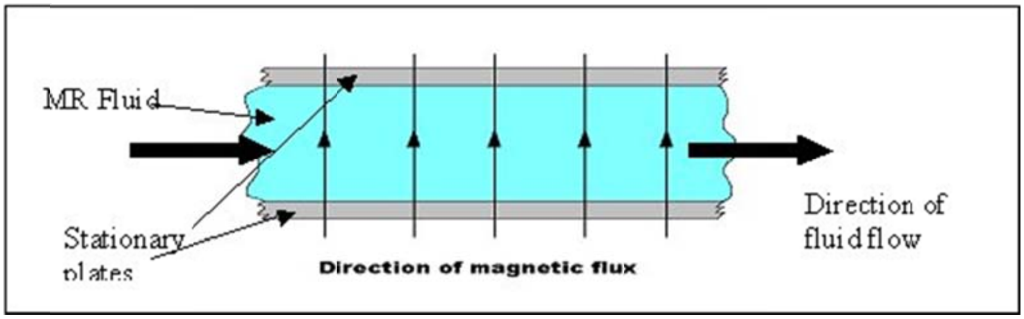
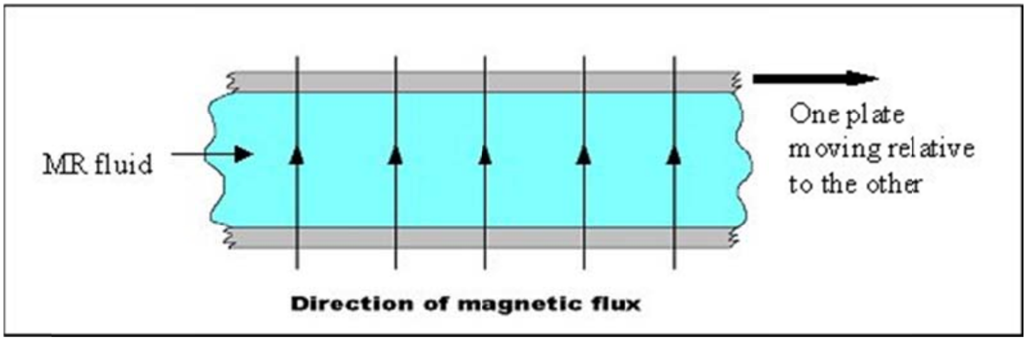


Fig. 8.29 Basic operating modes of electro- and magneto-rheological fluid devices (a) Valve mode (b) Direct shear mode (c) Squeeze-flow mode [Butz & Von Stryk, 2002]

Flow mode



Shear mode



Squeeze-flow mode

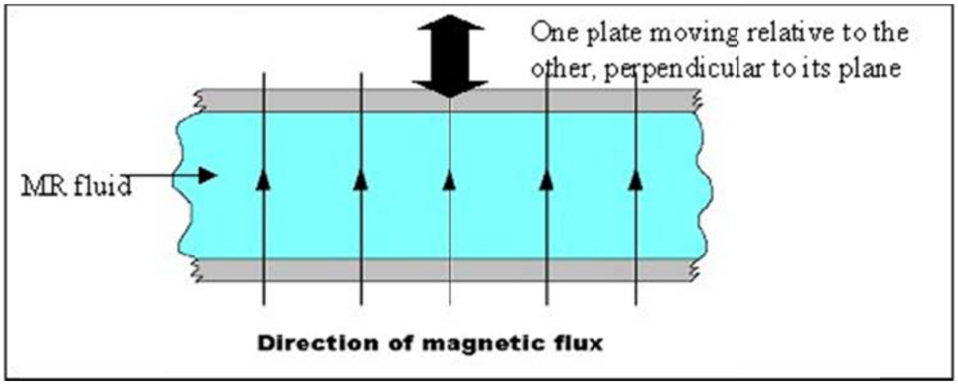


Fig. 8.30 Mode of operation of MR dampers

The applications of these various modes are numerous. Flow mode can be used in dampers and shock absorbers, by using the movement to be controlled to force the fluid through channels, across which a magnetic field is applied. Shear mode is particularly useful in clutches and brakes - in places where rotational motion must be controlled. Squeeze-flow mode, on the other hand, is most suitable for applications controlling small, millimeter-order movements but involving large forces. This particular flow mode has seen the least investigation so far. Overall, between these three modes of operation, MR fluids can be applied successfully to a wide range of applications. However, some limitations exist which are necessary to mention here.

Magneto-rheological (MR) Dampers:

Magneto-rheological (MR) dampers have recently become an object of intensive studies, both due to their interesting physical features, as well as due to their potential applicability to control damping in mechanical systems. The essential characteristic of MR fluids is their ability to reversibly change from free-flowing, linear viscous liquids to semi-solids having controllable yield strength in milliseconds when exposed to a magnetic field. This feature provides simple, quiet, rapid-response interfaces between electronic controls and mechanical systems. MR fluid dampers are new semi-active devices that utilize MR fluids to provide controllable damping forces. These devices overcome many of the expenses and technical difficulties associated with semi-active devices previously considered. The designed linear magneto-rheological damper is an actuator that allows controlling performance characteristics. The resisting force depends on piston speed and on strength of magnetic field in the working gap. MR fluid dampers are characterized by large damping force, low power consumption, etc. and may be used in various vibration control systems.

The structure of the damper has been developed on the basis of the analysis of strength properties and of dynamic phenomena for the concept adopted. This kind of damper usually uses the structure of a cylinder with a piston. The flow control (valve) for an MR fluid, which the magnetic field is applied to, is the orifice in the piston or individual bypass in the cylinder. According to their structure the dampers may be classified as single-ended piston-rod type and double-ended piston-rod type.

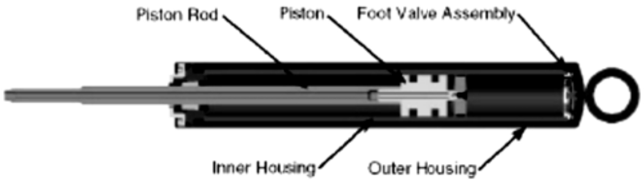


Fig. 8.31 Piston rod type MR damper

Mathematical models of MR dampers:

Mathematical models are represented by a mathematical function whose coefficients are determined rheologically, i. e., the parameter values are adjusted until the quantitative results of the model closely match the experimental data. Thus, the dynamic response of MR fluid devices is reproduced by a semi-empirical relationship. Numerous parametric models can easily be described by an arrangement of mechanical elements such as springs and viscous dashpots.

- Bingham model

Most commonly the behaviour of MR fluids is described by the Bingham plastic model. An ideal Bingham body behaves as a solid until a minimum yield stress τ_y is exceeded and then exhibits a linear relation between the stress and the rate of shear or deformation. Accordingly the shear stress τ developed in the fluid is given by

$$\tau = \tau_y \cdot \operatorname{sgn}(\dot{\gamma}) + \eta\dot{\gamma} \qquad (8.10)$$

where $\dot{\gamma}$ is the (shear) strain rate andη denotes the plastic viscosity of the fluid, i. e., the (Newtonian) viscosity at zero field (Gavin et al.).

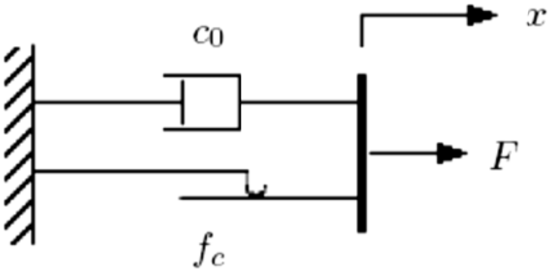


Figure 8.32: Bingham model (Spencer et al.)

The mechanical analogue, a Coulomb friction element in parallel with a viscous dashpot, is shown in Figure 8.32. In this model, the force F generated by the MR fluid device is given by,

$$F = f_c \cdot \operatorname{sgn}(\dot{x}) + c_0\dot{x} \qquad (8.11)$$

Where $x^{\cdot}$ denotes the velocity attributed to the external excitation, and where the damping coefficient c_0 and the frictional force f_c are related to the fluid’s viscosity and the field dependent yield stress respectively (Spencer et al.). The Bingham model accounts for electro- and magneto-rheological fluid behaviour beyond the yield point, i. e., for fully developed fluid flow or sufficiently high shear rates. However, it assumes that the fluid remains rigid in the pre-yield region.

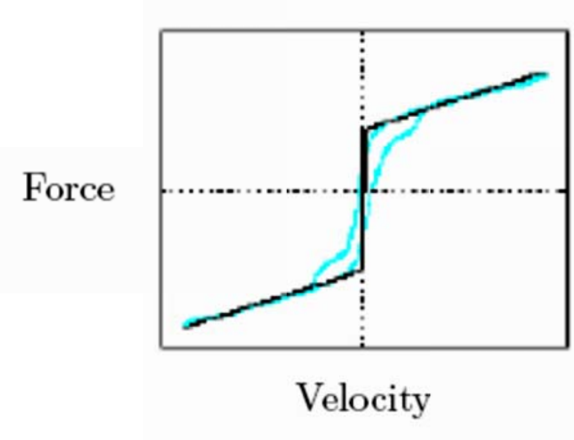


Fig. 8.33 Comparison between the predicted (_____) and the experimentally obtained (_____) force-velocity characteristic for the Bingham model (Spencer et al.)

- **Bouc-Wen model**

In their survey of phenomenological models Spencer et al. presented the so-called Bouc- Wen model in order to characterise the behaviour of a MR fluid damper. It is supposed to reproduce the response of hysteretic systems to random excitations

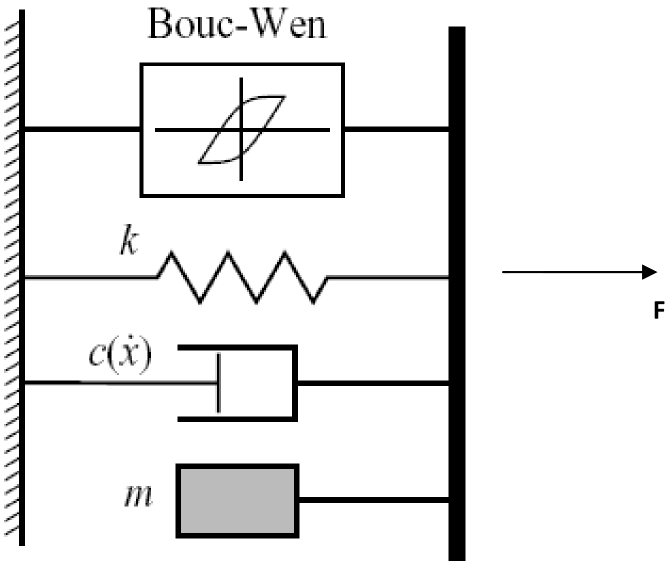


Fig. 8.34 Bouc-Wen Model (Spencer et al.)

A mechanical analogue of the Bouc-Wen model is shown in Figure 8.34. The force generated by the device is given by

$$F = c_0\dot{x} + k_0(x - x_0) + \alpha z \qquad (8.12)$$

where the hysteretic component z satisfies

$$\dot{z} = -\gamma \left|\dot{x}\right| z \left|z\right|^{n-1} - \beta\dot{x}\left|z\right|^{n} + \delta\dot{x}. \qquad (8.13)$$

By adjusting the parameter values α, β, γ, δ and *n* it is possible to control the shape of the force-velocity characteristic; an initial displacement x_0 of the spring was incorporated into the model to allow for the presence of an accumulator in the considered damper.

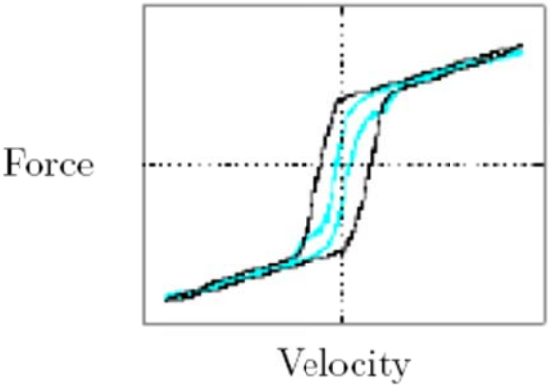


Fig. 8.35 Comparison between the predicted (_____) and the experimentally obtained (_____) force-velocity characteristic for the Bingham model (Spencer et al.)

APPLICATIONS

The application set for MR fluids is vast, and it expands with each advance in the dynamics of the fluid.

Mechanical engineering

Magneto-rheological dampers of various applications have been and continue to be developed. These dampers are mainly used in heavy industry with applications such as heavy motor damping, operator seat/cab damping in construction vehicles, and more.

As of 2006, materials scientists and mechanical engineers are collaborating to develop stand-alone seismic dampers which, when positioned anywhere within a building, will operate within the building's resonance frequency, absorbing detrimental shock waves and oscillations within the structure, giving these dampers the ability to make any building earthquake-proof, or at least earthquake-resistant.

Military and defense

The U.S. Army Research Office is currently funding research into using MR fluid to enhance body armor. In 2003, researchers stated they were five to ten years away from making the fluid bullet resistant. In addition, Humvees, and various other all-terrain vehicles employ dynamic MR shock absorbers and/or dampers.

Magneto-rheological finishing, a magneto-rheological fluid-based optical polishing method, has proven to be highly precise. It was used in the construction of the Hubble Space Telescope's corrective lens.

Automotive and aerospace

If the shock absorbers of a vehicle's suspension are filled with magneto-rheological fluid instead of plain oil, and the whole device surrounded with an electromagnet, the viscosity of the fluid, and hence the amount of damping provided by the shock absorber, can be varied depending on driver preference or the weight being carried by the vehicle - or it may be dynamically varied in order to provide stability control. This is in effect a magneto-rheological damper. For example, the MagneRide active suspension system permits the damping factor to be adjusted once every millisecond in response to conditions. General Motors (in a partnership with Delphi Corporation) has developed this technology for automotive applications. It made its debut in both Cadillac (Seville STS build date on or after 1/15/2002 with RPO F55) as "Magneride" (or "MR") and Chevrolet passenger vehicles (All Corvettes made since 2003 with the F55 option code) as part of the driver selectable "Magnetic Selective Ride Control (MSRC)" system) in model year 2003. Other manufacturers have paid for the use of it in their own vehicles. As of 2007, BMW manufactures cars using their own proprietary version of this device, while Audi and Ferrari offer the MagneRide on various models.

General Motors and other automotive companies are seeking to develop a magneto-rheological fluid based clutch system for push-button four wheel drive systems. This clutch system would use electromagnets to solidify the fluid which would lock the driveshaft into the drive train.

Porsche has introduced magneto-rheological engine mounts in the 2010 Porsche GT3 and GT2. At high engine revolutions, the magneto-rheological engine mounts get stiffer to provide a more precise gearbox shifter feel by reducing the relative motion between the power train and chassis/body.

As of September 2010, Acura (Honda) has begun an advertising campaign highlighting its use of MR technology in passenger vehicles manufactured for the 2011 model year.

Magnetorheological dampers are under development for use in military and commercial helicopter cockpit seats, as safety devices in the event of a crash. They would be used to decrease the shock delivered to a passenger's spinal column, thereby decreasing the rate of permanent injury during a crash.

Human prosthesis

Magnetorheological dampers are utilized in semi-active human prosthetic legs. Much like those used in military and commercial helicopters, a damper in the prosthetic leg decreases the shock delivered to the patients leg when jumping, for example. This results in an increased mobility and agility for the patient.

Source:http://nptel.ac.in/courses/112107088/32