UTM Faculty of Mechanical Engineering UNIVERSITI TEKNOLOGI MALAYSIA THE ENGINEER STORY

e-ISSN: 3009 - 0792 Volume 18, 2025, 28-31

SMART MATERIALS: AN OVERVIEW OF THE MAGNETORHEOLOGICAL (MR) EFFECT

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ABSTRACT

Magnetorheological (MR) materials such as MR fluids, MR elastomers and MR greases, show rapid and reversible changes in their mechanical properties when exposed to a magnetic field. This behaviour, known as the MR effect, allows significant changes in yield stress, viscosity and stiffness, enabling their use in many engineering applications. This paper provides a simple overview of the MR effect, including its definition, how it is measured and the mechanisms behind particle alignment under a magnetic field. Key applications in automotive systems, structural control, robotics, defence and medical devices are highlighted. The paper also discusses current challenges and future research opportunities in advancing MR materials and technologies.

KEYWORD

Magnetorheological effect, smart materials, yield stress enhancement, MR fluid, MR elastomer

INTRODUCTION

Magnetorheological (MR) materials belong to a wider class of smart materials capable of altering their mechanical behaviour in response to external stimuli. MR materials can generally be classified into three main categories: MR fluids, MR elastomers and MR greases, each distinguished by its physical state, structural characteristics and performance behaviour under a magnetic field. MR fluids are composed of micron-sized magnetic particles suspended in a carrier liquid, forming a flowable medium that responds rapidly to magnetic stimulation. Their ability to change viscosity and yield stress almost instantaneously makes them suitable for devices requiring fast actuation, although issues such as sedimentation and sealing remain practical challenges. In contrast, MR elastomers are solid or semi-solid composites in which magnetic particles are embedded within an elastomeric matrix. Unlike MR Fluids, MR elastomers do not suffer from leakage or severe sedimentation, and their stiffness can be tuned through both the applied magnetic field and the mechanical characteristics of the matrix, making them attractive for vibration isolation and adaptive stiffness applications.

MR greases occupy an intermediate state between fluids and elastomers, they consist of magnetic particles dispersed within a grease-like carrier medium, resulting in a semi-solid system with improved stability and reduced sedimentation compared to conventional MR fluids. MR Greases offer the advantages of high field-induced performance and enhanced durability under shear, making them suitable for applications where leakage resistance and long-term operational stability are essential. Together, these three classes of MR materials provide a diverse range of field-responsive behaviours, enabling their use across a wide spectrum of engineering systems.

Among various field-responsive materials, MR systems stand out because of their fast response, low power requirement and high controllability under magnetic fields. The MR effect enables these materials to transition from a liquid-like or soft state to a semi-solid or stiff state within milliseconds. The MR effect refers to the change in rheological properties including viscosity, yield stress, storage modulus, loss modulus and shear resistance, when a magnetic field is applied. Magnetic particles within the material become polarized and form chain-like structures aligned along the field direction, resulting in an increase in stiffness or resistance to deformation. This transformation is reversible and controllable, where the mechanical behaviour can be repeatedly tuned by varying the external magnetic field intensity. In characterizing MR behaviour, two complementary metrics are typically used, the **absolute MR effect**, indicating the direct field-induced change in properties such as yield stress or modulus, and the **relative MR effect**, which represents the proportional or percentage increase relative to the baseline state. This paper provides a simple but comprehensive overview of the MR effect, its measurement methods and its applications.

METHODS TO CALCULATE MR EFFECT

The MR effect can be evaluated through several rheological parameters, depending on the type of MR material and its intended application. One of the most widely used approaches is based on yield stress. In this method, the MR effect is described either as the **absolute MR effect**

$$\Delta\tau_y = \tau_{y,H} - \tau_{y,0} \tag{1}$$

or as the **relative MR effect**

$$(\tau_{y,H} - \tau_{y,0})/\tau_{y,0} \times 100\% \tag{2}$$

where $\tau_{y,H}$ and $\tau_{y,0}$ represent the yield stress values in the presence and absence of a magnetic field, respectively. This yield stress–based evaluation is commonly used in the design of MR dampers, brakes and other devices that operate under shear-dominant conditions. In addition to yield stress, the viscosity of MR fluids can also be used to quantify the MR effect. When a magnetic field is applied, the viscosity changes significantly and this effect is often expressed as the viscosity ratio η_H/η_0, where η_H and η_0 denote the viscosities under field-on and field-off conditions. This method is useful for applications involving continuous flow or varying shear rates, as it captures the field-induced alteration in flow resistance.

For MR elastomers, modulus-based calculations are more relevant. The change in storage modulus, $\Delta G' = G'_H - G'_0$, provides a direct measure of the stiffness enhancement due to magnetic stimulation. A corresponding relative modulus change may also be used to compare different material formulations or particle loadings. This approach is particularly important for vibration control and adaptive stiffness applications. In some cases, the MR effect is evaluated through shear stress or flow-curve analysis, where the stress response at a constant shear rate is compared between field-on and field-off states. The area under the flow curve can also be used to define an energy-based MR index, providing insight into the overall resistance contributed by the magnetic field. For MR elastomeric materials, the MR effect under dynamic or oscillatory loading is typically evaluated by measuring changes in the storage modulus, loss modulus, and the resulting loss factor. These parameters describe how the applied magnetic field alters the material's stiffness and damping behaviour during cyclic deformation. Such dynamic evaluations are crucial for systems exposed to periodic excitations, including automotive suspensions, seismic control devices and wearable rehabilitation technologies.

MECHANISM UNDERLYING THE MR EFFECT

The MR effect originates from the field-induced reorganization of magnetic particles within the material, a process well illustrated in Figure 1. In the absence of a magnetic field, the particles remain randomly dispersed throughout the carrier medium and the material exhibits low resistance to deformation. When a magnetic field is applied, these particles become magnetized and interact through dipole-dipole forces, aligning into chain-like or columnar structures in the direction of the magnetic flux. The formation of these structures significantly increases the material's ability to resist shear, resulting in higher yield stress, enhanced viscosity or increased modulus depending on the type of MR system.

In MR fluids, the mobility of suspended particles enables rapid and reversible structural formation, giving these systems their characteristic fast response time. In contrast, MR elastomers exhibit a more constrained but stable response because the particles are embedded within a solid elastomeric matrix; here, the magneto-mechanical behaviour depends not only on particle interactions but also on matrix stiffness, crosslink density and particle–matrix interfacial adhesion. The magnitude of the magnetic field plays a crucial role in strengthening these induced structures-stronger fields produce more rigid particle chains until magnetic saturation is approached, beyond which additional increases in field intensity result in negligible changes in mechanical response.

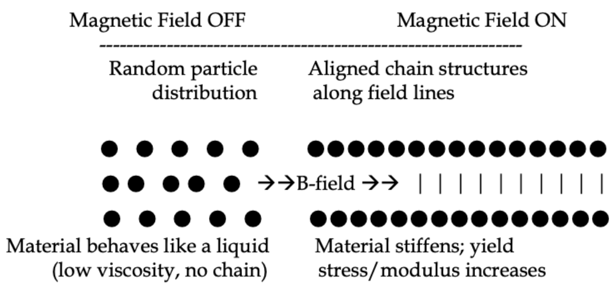

Figure 1: Basic mechanism of the MR effect

Environmental conditions and long-term stability also influence the underlying MR mechanism. Sedimentation or particle agglomeration in MR fluids may reduce homogeneity and disrupt uniform chain formation, while temperature fluctuations and repeated cyclic loading can affect the durability and bonding characteristics of MR elastomers. Collectively, these microstructural processes and external influences govern the overall magneto-mechanical performance of MR materials and determine their suitability for various engineering applications.

APPLICATIONS OF THE MR EFFECT

The MR effect has enabled the development of a wide range of adaptive and controllable devices across several engineering disciplines. In the automotive and transportation sector, MR technology is most prominently applied in semi-active shock absorbers, engine mounts and seat vibration control systems. These devices exploit the rapid field-dependent change in damping characteristics to improve ride comfort, vehicle handling and overall safety. In civil and structural engineering, MR dampers are widely used for seismic protection and vibration mitigation in bridges and buildings. Their ability to adjust stiffness and energy dissipation in real time allows structures to respond more effectively to dynamic loads such as earthquakes, wind and human-induced vibrations.

In the field of robotics and human–machine interaction, MR materials are incorporated into haptic feedback devices, MR brakes, MR clutches and variable stiffness actuators. These components provide precise, smooth, and responsive force control, which is essential for safe interaction between robots and human users. The defence and aerospace industries also benefit from MR-based solutions, utilizing them in recoil reduction systems, adaptive landing gear and vibration attenuation platforms, where reliability, rapid response and robustness are critical operating requirements. Furthermore, the medical and rehabilitation sectors have increasingly adopted MR technology in devices such as prosthetic knees employing MR brakes, adjustable orthotic supports and rehabilitation robots designed to offer controllable resistance during therapeutic exercises. These applications take advantage of the MR effect's ability to deliver smooth, controllable and non-mechanical resistance, enhancing user comfort and functional performance. Collectively, these diverse applications demonstrate the versatility and engineering impact of MR materials across modern technological systems.

CHALLENGES AND FUTURE PERSPECTIVES

Although MR materials have achieved substantial technological advancements, several challenges continue to limit their broader implementation in commercial and high-performance systems. One of the primary issues is sedimentation and long-term stability in MR fluids, where the density mismatch between magnetic particles and the carrier liquid leads to particle settling and reduced performance consistency. Additionally, the limited magnetic saturation of commonly used particle materials constrains the maximum achievable MR effect, while heat generation during high-frequency or high-load operation can further degrade performance and shorten device lifespan. In the case of MR elastomers, material fatigue and degradation under repeated cyclic loading pose concerns for durability, particularly in applications requiring long-term reliability. Another persistent challenge is the need for miniaturized, low-power magnetic actuation systems, which are essential for integrating MR technologies into compact or portable devices.

Looking ahead, several promising research directions may help address these limitations and expand the applicability of MR materials. The integration of artificial intelligence and advanced control algorithms is expected to enhance real-time adaptability and system responsiveness, especially in applications involving complex dynamic environments. Advances in particle surface engineering and functional coatings may improve dispersion stability, reduce sedimentation and increase overall MR performance. Emerging manufacturing approaches, such as 4D printing, open opportunities for fabricating MR materials with customizable architectures and dynamic, reconfigurable properties. Furthermore, the development of hybrid MR materials that combine multiple smart functionalities such as magneto-electric, magneto-thermal or magneto-photonic responses could significantly broaden the range of applications and enable next-generation adaptive systems. Together, these advancements highlight both the challenges and the exciting potential of MR technologies in future engineering innovations.

CONCLUSION

This paper has reviewed the main aspects of the MR effect, including the types of MR materials, how their properties change under a magnetic field and how this effect can be measured. The ability of MR materials to quickly vary their mechanical behaviour makes them useful in many applications, from vehicle suspension systems to medical and robotic devices. Although MR technology has progressed well, issues such as sedimentation, limited magnetic saturation and material fatigue continue to pose challenges. Future improvements in material design, manufacturing methods and control systems are expected to enhance the performance and broaden the use of MR-based devices.

ACKNOWLEDGEMENT

This study was supported by Higher Institution Centre of Excellence (HICoE) Research Grant under Ministry of Higher Education (MOHE) Malaysia

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