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Review Magnetorheological Fluids and their Automotive Applications

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Abstract - Magnetorheological fluids (MRF) are smart materials whose rheological properties can be rapidly and reversibly controlled by applying a magnetic field. This review explores the fundamental composition and operating principles of MRF and highlights their transformative potential in automotive systems. Composed of carrier fluids, magnetic particles, and stabilizing additives, MRFs exhibit variable viscosity that can transition from a liquid to a semi-solid state under magnetic influence. The paper classifies the operational modes of MRF-based actuators—flow, shear, and squeeze modes—and discusses their respective applications in brakes, clutches, and dampers. Particular emphasis is placed on recent advances in MR brake and clutch designs tailored for motorcycles, wheelchairs, and active suspension systems. Similarly, MR dampers are shown to significantly improve ride comfort, driving stability, and vibration control in vehicle suspensions and seat systems. The review underscores the advantages of MRF technology, such as fast response time, low power consumption, and fail-safe operation, while acknowledging design challenges related to magnetic circuit integration. Ultimately, the study affirms the growing relevance and adaptability of MRFs in the evolution of smart automotive systems.

Key Words: Magnetorheological fluids (MRF); MR brakes; MR clutches; MR dampers

1.INTRODUCTION

Approximately 60 years ago, in the 1940s, Jacob Rabinov discovered the Magnetorheological Fluids (MRF) effect at the US National Bureau of Standards. A magneto-rheological-fluid is a fluid with rheological behaviour which depends on the strength of a magnetic field. The rheological status changes reversibly from liquid to the solid. The Greek word ‘‘rheos’’ means flowing and rheology is the science of deformation behaviour of materials which are able to flow.Normally the rheological property of viscosity changes with other physical properties, such as chemical composition, shear stress and temperature. These features are not easily controlled in most applications because they are fixed by the environment in a particular situation. In the case of all fluids the variation of viscosity with temperature is reversible but this does not allow the viscosity to be controlled easily. In the case of MR the fluid viscosity becomes intelligently controllable using the magnetic field. This change of viscosity up to the solid condition is reversible and is the basic feature of MRF technology. The MRF effect is the difference in rheological properties with and without a magnetic field [1].

There are basically three components in an MR fluid: basic fluid, metal particles and stabilizing additives [2–17]. The base fluid has the function of the carrier and naturally combines lubrication (in combination with additives) and damping features. For the highest MRF effect the viscosity of the fluid should be small and almost independent of temperature. In this way the MRF effect will be the dominant effect when it is compared with the natural physical viscosity varying with temperature and shear stress [1].

Basically in the off-state (without any magnetic effects) MR fluids behave like the base fluid in accordance with their chemical compositions. There are different types of liquid which can be used as the carrier fluid i.e. hydrocarbon oils, mineral oils or silicon oils. As with any type of particle suspended in a fluid, the base fluid will have a higher viscosity when the concentration of metal particles is very high. The fluid will appear to be ‘‘thicker’’ [6]. So even in the off-state, the fluid with the powder will have an increased viscosity. Usually the dynamic viscosity gd at ambient temperature is around 100 mPa [8].

In the on-state (with a magnetic field in place) the metal particles are guided by the magnetic field to form a chainlike structure. This chain-like structure restricts the motion of the fluid [5] and therefore changes the rheological behaviour of the fluid. The MR-effect is produced because of this resistance to flow caused by the chain-like structure. The metal particles are usually made of carbonyl iron, or powder iron, or iron/cobalt alloys to achieve a high magnetic saturation. The amount of metal powder in MRF can be up to 50% by volume [2–17]. The particle size is in the l-meter range and varies depending on the manufacturing processes. The particle size can be chosen to achieve various purposes. In the case of carbonyl iron the particle size ranges between 1 and 10 lm. Larger particles and higher fractions of powder in the MR fluid will provide higher torque in the onstate, but at the same time the viscosity of the MR fluid in the off-state will also be higher under these conditions.
The material specification, especially the permeability is also a very important factor for controlling the MR-effect [1].

The additives include stabilizers and surfactants [8]. Additives are suspending agents, thixotropes, friction modifiers and anti-corrosion/wear components. Highly viscous materials such as grease or other thixotropic additives are used to improve settling stability [14]. Ferrous naphthanate or ferrous oleate can be used as dispersants and metal soaps such as lithium stearate or sodium stearate as thixotropic additives [15]. Additives are required to control the viscosity of the liquid and the settling rate of the particles, the friction between the particles and to avoid the in-use thickening for a defined number of off-duty cycles.

All three components define the magneto-rheological behaviour of the MR fluid. The total density depends on the formulation and is approximately by 3–4 g/cc. The change of one of the MRF components will lead to rheological changes (in the off-state) and to magneto-rheological changes in behaviour (in the on-state). Finally a trade-off between the achievable performances of all three components in combination is required in order to optimise a formulation [1].

2. MRF operational Mode

The operation modes of a MR actuator can be classified into flow, shear, and squeeze modes. The conceptual configuration of each mode is illustrated in Figure 1. In the flow mode, as shown in Figure 1a, the MR fluid fills the space between two stationary plates and flow occurs due to the result of the pressure difference between the two ends. A magnetic field is applied perpendicular to the flow. A damper is the most representative type of actuator that utilizes the flow mode. In the shear mode, as shown in Figure 1b, the MR fluid fills the space between a stationary plate and a sliding plate, and a magnetic field is applied in a direction perpendicular to the moving plate. For the plate to move, the chain structure formed in the MR fluid must break. The force that breaks the chain structure is expressed as an actuating force. Brakes and clutches are typical actuators that use the shear mode. In the squeeze mode, as shown in Figure 1c, the MR fluid fills the space between two moving plates. A magnetic field is applied in the same direction as the moving direction of the plates and flow occurs perpendicular to the moving direction of the plates. The squeeze mode is suitable for cases in which the displacement is small, but a large actuating force is required and is typically utilized in dampers or mounts. Actuators such as dampers, brakes, clutches, and mounts are representative devices in which MR fluid are applied. Actuators using MR fluid have the disadvantage of having to design a magnetic core for generating a magnetic field, but they have many advantages such as fast response times (less than 1 ms), low power consumption (less than 5 W for a vehicle damper), and simplicity of structural design. A unique advantage of MR actuators is that they can exhibit failsafe features without requiring additional devices, unlike conventional active actuators such as motors or passive actuators such as hydraulics. These advantages are attractive for utilizing MR actuators in various industries such as automotive engineering, aerospace engineering, manufacturing engineering, and civil engineering [18].

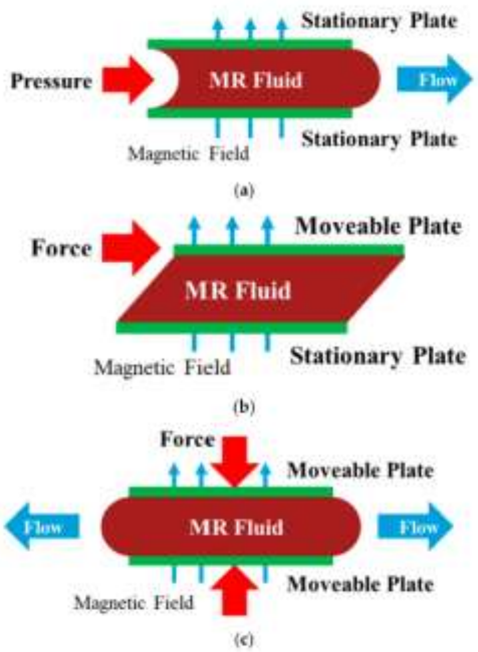

Figure 1. Conceptual configuration of the operating modes of a MR actuator. (a) Flow mode; (b) shear mode; (c) squeeze mode [18].

3. MR Brake/ Clutch

MR brakes and clutches are actuators that can control torque on a rotating device. The purpose of the MR brake is to reduce the rotation speed or stop rotation completely to transmit the rotational force from one shaft to another shaft. A MR brake is configured in the form of a fixed housing and rotating core, and the MR fluid fills the space between the core and the housing. A MR clutch consists of one pair of rotating cores, another individual rotating core, and a rotating housing. The MR fluid fills the space between the cores or between the core and the housing. A core is designed in the form of a disk or drum, and the MR effect is generated in the MR fluid in the flow mode or the shear mode. The schematic configurations of a MR brake and clutch are presented in Figure 2. Phu and Choi presented a mini-review article on MR brakes and clutches reported from 2013 to 2018 with a focus on their structural configurations [19]. Hua et al. reviewed the state of the art based on the structural configurations of MR brakes and clutches developed between 2018 and 2021 [20]. In this section, MR brakes and clutches developed from 2015 to 2021 are summarized according to their fields of application.

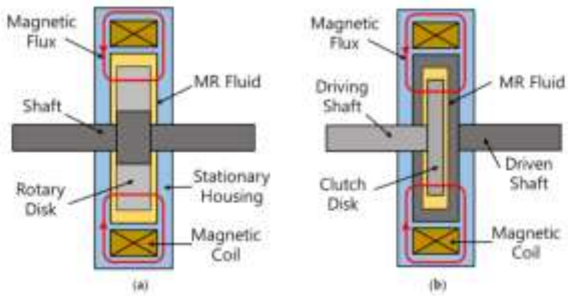

Figure 2. Schematic configurations of MR brakes and clutches. (a) MR brake; (b) MR clutch [18].

In an effort to apply MR brakes and clutches in the vehicle-engineering field, various studies have been conducted, and many have been reported in recent years. Sohn et al. [21] proposed a single-disc-type MR brake for midsize motorcycle applications, as shown in Figure 3. Design parameters such as the radius of the disc, the gap size, and the coil dimensions were optimized through finite element analysis, and the braking torque of the manufactured MR brake was evaluated experimentally. Yu et al. [22] presented a new design for a MR brake featuring a multipath magnetic circuit using permanent magnets to achieve enhanced braking torque for vehicle applications. After determining the design parameters through finite element analysis and experiments on the fabricated prototype, a full-scale prototype was fabricated, and its feasible application in automotive braking was validated. However, based on the large size of the proposed MR brake model, its practical realization and maintenance are difficult. Shamieh and Sedaghati [23] formulated a multidisciplinary design-optimization problem to identify the optimal geometrical parameters of a MR brake to improve the slipping of vehicles under different road conditions. After solving the optimization problem, the performance of an optimally designed MR brake
was investigated using a quarter-vehicle model. Le et al. [24] conducted design-parameter optimization on a MR brake for motorcycle applications with multiple objectives, including maximizing braking torque, minimizing brake mass, and limiting the temperature to below a critical value. They considered the design of rectangular and polygonal-shaped housings and side-coil configurations. In addition, they compared the braking performance of different models. Hasannasab and Bazargan-Lari [25] designed and manufactured a MR brake for wheelchair

handling under low-weight constraints. Based on finite-element-analysis results, a prototype was manufactured, and its braking performance was evaluated by confirming good agreement between the experimental- and numerical-analysis results. Le et al. [26] developed a MR brake featuring a rotating disc with multiple trapezoidal teeth for small motorcycle applications. To obtain a high braking torque, multiple poles with trapezoidal shapes were adopted, and the size of the brake was kept compact. Tri et al. [27] developed a MR brake for application in a cycling training system. They adopted a dual disc and a dual coil to obtain a higher braking torque by increasing the contact area between the MR fluid and the disc. After optimizing the design parameters, a prototype was fabricated; its braking performance was validated; and good agreement between the experimental and numerical simulation results was confirmed. Wang et al. [28] proposed a multidisc MR clutch for vehicle applications. To overcome the high-temperature problem that degrades the performance of MR clutches in vehicle applications, the transient temperature was investigated through experiments and numerical simulations. East et al. [29] presented a new application of a MR clutch to an automotive active suspension system. They compared the experimental results to those of previous studies and verified that an active suspension system that can efficiently control vibrations can be constructed by applying a MR clutch to a suspension consisting of an electric motor, rack, and pinions. Lokhande and Patil [30] designed and manufactured a MR clutch for two-wheeled electric-vehicle applications. The torque transmission capabilities of the MR clutch with and without slits were evaluated analytically and experimentally, and an increase in torque transmission caused by the presence of slits was validated.

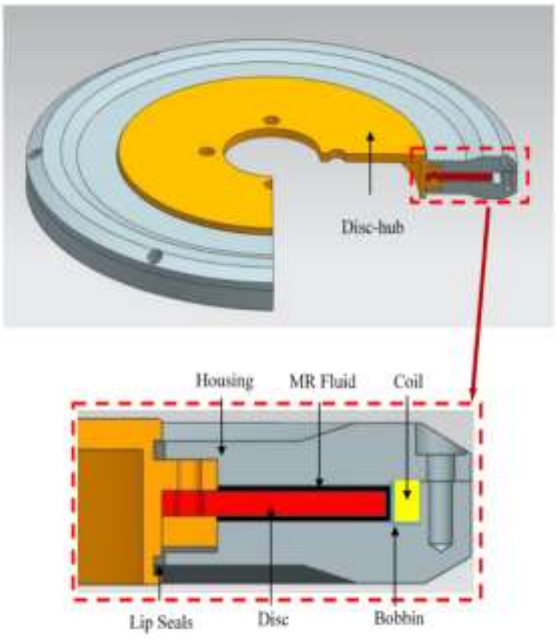

Figure 3. A single-disc-type MR brake for midsize motorcycles [21].

4. MR Damper

The damping force of a MR damper is tuned by adjusting the magnetic field intensity under various road conditions. Therefore, the desired damping force for a multi-DOF vehicle system can be achieved using a MR damper, thereby providing both ride comfort and driving stability. The advantages of MR dampers include their simple mechanism, lack of moving parts, high reliability, and excellent durability. As shown in Figure 4, Cadillac and Audi have released various sports-car models with MR dampers.

Figure 4 commercialized products for vehicle suspension (Cadillac Touring 6) [18].

Recently, MR dampers have been used to reduce not only vertical motion but also steering motion [31,32]. Dutta et al. defined a 3-DOF dynamic model of the Macpherson strut with a MR damper, rotation of the wheel assembly, and lateral stiffness of the tire to represent the nonlinear characteristics of a Macpherson-type suspension system [31]. Additionally, a novel type of controller for regulating 4-DOF steering motions such as shimmy vibration was developed, and its control performance was evaluated [32]. To enhance ride comfort and reduce unwanted vibrations, a novel adaptive sliding mode controller was proposed by adopting a moving sliding surface. MR dampers can be applied to the seat suspensions of heavy dump trucks or buses [33]. Ride quality in heavy dump trucks or buses is very important based on its effects of safety and health issues for drivers. Therefore, a rotary-type MR seat damper was devised to reduce the transmitted vibration from the ground and increase the productivity of drivers. Additionally, Phu et al. [34,35] proposed a novel adaptive fuzzy controller associated with the H-infinity technique for 2-DOF vehicle seat suspension, as shown in Figure 5. When using an adaptive controller, vibration control performance was significantly better than that when using a fuzzy controller.

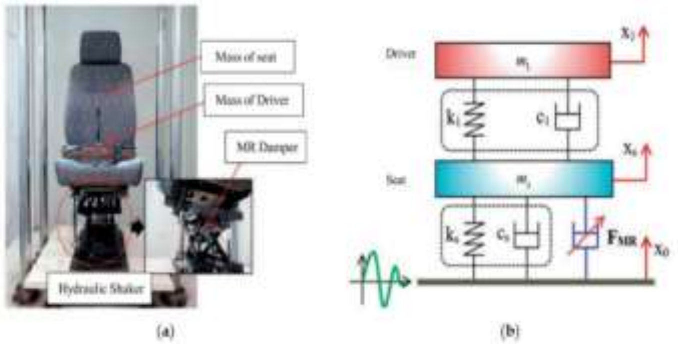

Figure 5. Schematic configuration of a MR seat suspension for 2-DOF seat system [35]. (a) Photograph; (b) mechanical model [18].

5. CONCLUSIONS

In this review articles, MR fluid, MR brakes, MR clutches and MR dampers were adopted and discussed. Based on the inherent and salient properties of MR fluid, the research progress in the development of MR applications has become very fast, and the research topics are still active and attractive. The magneto-rheological-fluid (MRF) technology is one of the old ‘‘newcomers’’ coming to the market at high speed. The world is full of potential MRF Automotive applications.

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