Research and Applications of MR Elastomers

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Abstract: Magnetorheological elastomer (MRE) is a new branch of MR materials, which are smart materials whose rheological properties can be controlled by the application of an external magnetic field. MREs are solid, rubber-like materials whose modulus can be adjusted by applying magnetic field. In this article, the current research and patents on the material fabrication, modeling and testing, and applications will be reviewed and discussed. As the articles review, recent interesting in applications focused on three main areas. The first one is on the sound and vibration control, especially on the vehicle applications, including dynamic vibration absorber and isolator. The second one is on the controllable stiffness change and deformation, such as roll in papermaking machine and releasable fastener system. The third one is on the sensors and actuators. In summary, MREs have made significant advances and will have promising applications.

Keywords: Magnetorheological elastomers, field-dependent modulus, rheological properties.

1. INTRODUCTION

Magnetorheological (MR) material is a class of smart materials whose rheological properties can be controlled rapidly and reversibly by the application of an external magnetic field. Traditionally, it is composed of MR fluids and MR foams, while Magnetorheological elastomers (MREs) became a new branch of this kind of smart material. MR materials typically consist of micron-sized magnetic particles suspended in a non-magnetic matrix. The magnetic interactions between particles in these composites depend on the magnetization orientation of each particle and on their spatial relationship, coupling the magnetic and strain fields in these materials and giving rise to a number of interesting magneto-mechanical phenomena [1-8].

In MR fluids, iron particles are suspended in a liquid carrier fluid. MR foams, in which the controllable fluid is contained in an absorptive matrix or magnetic particles are dispersed in a foam-like matrix, are solid-state materials with very low intrinsic modulus. MREs are composites where magnetic particles are suspended in a non-magnetic solid or a gel-like matrix. The particles inside the elastomer can be homogeneously distributed or they can be grouped (e.g. into chain-like columnar structures). To produce an aligned particle structure, the magnetic field is applied to the polymer composite during crosslinking so that the columnar structures can form and become locked in place upon the final cure. This kind of processing imparts special anisotropic properties to the viscoelastic materials. Only recently has the field responsiveness of the viscoelastic properties of these elastomers been explored [9-17].

Although MR materials have many analogical mechanical behaviors, MREs have a unique mechanical performance different from other materials: MREs have a controllable, field-dependent modulus while MR fluids and MR foam have a field-dependent yield stress [18-20]. This makes the two groups of materials complementary rather than competitive to each other. In other words, the strength of MR fluids is characterized by their field dependent yield stress while the strength of MREs is typically characterized by their field dependent modulus.

The applications can benefit from these materials whose rheology can be continuously, rapidly and reversibly varied are numerous [2-5]. MR fluids' field-dependent yield stress makes them to be widely used in various smart devices, such as dampers, clutches, and brakes. Although currently there is few report on applications of elastomers with controllable rheology because the research on MREs is still at a primary stage, there is little doubt that there are numerous applications that can make use of controllable stiffness and others unique characteristics of these elastomers, such as adaptive tuned vibration absorbers (TVAs), tunable stiffness mounts and suspensions, and variable impedance surfaces [2, 4].

Other obvious advantages of MREs are that the particles are not able to settle with time and that there is no need for containers to keep the MR material in place [21]. Because the chain-like or columnar structures have been locked in the rubber-like matrix during curing, the particles need no time to arrange again while MREs are applied an external magnetic field, thus the response time of MREs is much less than that of MR fluids (several ms).

2. MATERIALS

In general, the particles used in MR materials are magnetizable ferromagnetic, low coercivity (i.e., little or no residual magnetism when the magnetic field is removed), finely divided particles of iron, nickel, cobalt, iron-nickel alloys, iron-cobalt alloys, iron-silicon alloys and the like which are spherical or nearly spherical in shape and have a diameter in the range of about 1 to 100 microns. A preferred material is the particulate iron microspheres known as

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carbonyl iron. Since the particles are employed in non-colloidal suspensions, it is preferred that the particles be at the small end of the suitable range, preferably in the range of 1 to 10 microns in nominal diameter or particle size to avoid sedimentation, although the MR materials with larger size particles generally have larger MR effect [22]. But for MR elastomer, the sedimentation has been overcome. Thus the particle size in MREs has a larger range of choice. There were many patents about the improved particles for MR materials. For example, in US20050064191, hydrophobic metal particles that are useful as the magnetizable particles in MREs are provided [23]. Hydrophilic metal particles, such as carbonyl iron particles, are made hydrophobic by reacting a surface hydroxyl on the solid metal particle with a reactive surfactant. Particles are coated with the reactive surfactant to cover at least about 90% of the surface of the particles and then washed with a low viscosity synthetic hydrocarbon to remove any excess surfactant. The particles are stabilized against oxidation and irreversible coagulation during further processing, and formulation and use in magnetorheological materials.

The matrix of MR elastomers also has lots of choice, such as thermoplastic rubber, silicone rubber, plastic, natural rubber and synthetic rubber, and so on. Among them, natural rubber has very good mechanical properties, flexibility and processing performance. It is very suitable for the practical MR elastomer [24-28]. And butyl rubber has excellent chemical stability and insulation and high damping factor, so it is suitable for MR elastomer based shock absorber. In addition, the silicone rubber and thermoplastic rubber have been widely used to prepare MR elastomer in lab because they are easy to be processed [24-32]. The other matrices include acrylonitrile rubber [9, 10], vinyl PVA glutaraldehyde synthetic polymers [33], polyurethane - oxygen fluorine polymer [31], polyurethane [11] and formaldehyde plastic [8]. These show that the matrix choice of MR elastomer is very flexible. For example, in US20036527972, the polymer gel was used to prepare MREs too. It comprised magnetic particles, a polymeric gel and a carrier material also have magnetic field-dependent rheological behavior [34].

The amount of magnetizable particles should be sufficient to provide the required on-state mechanical properties, preferably 50-90%, more preferably 60-80% weight percent, based on the total weight of the MR material. MR elastomers are commonly prepared by using a strong constant and uniaxial magnetic field. Magnetic particles are mixed with a matrix with a certain volume fraction. When individual particles are exposed to an applied magnetic field, magnetic dipole moments pointing along the magnetic field are induced in the particles. Pairs of particles form head-to-tail chains. When the matrix is cured, the particles are locked into place and the chains are embedded in the matrix. At Ford Research Laboratory, Ginder *et al.* [2, 4, 5] developed such materials composed of natural or synthetic rubber filled with micron-sized iron particles. Zhou [20] and Shen *et al.* [11] prepared MREs using the same method, while using the silicone rubber as matrix. Lokander [9, 10] *et al.* used large size iron particles with irregular shape to prepare isotropic MREs. Other additives were also used to improve the mechanical behavior of MREs. For example, in reference [35], the influence of carbon black was investigated and the experimental results demonstrate that carbon black plays a significant role in improving the mechanical performance of MR elastomers. Besides the merits of high MR effect and good tensile strength, the damping ratio of such materials is much reduced. In US20050116194 and US20077261834 [36, 37], they introduced some MREs and methods for their manufacture. The prepared MREs can have improved oxidative resistance, thermal oxidative resistance, high temperature resistance, ozone resistance, moisture resistance, and seawater resistance. The methods include the coating of the magnetizable particles for corrosion protection and/or improvement of the bonding between the particle and the matrix, different matrix choices and the curing magnetic flux control.

3. MODELS AND PROPERTIES

A number of models have been developed to describe MRE performances. Accurate models can predict the performance of MR elastomers in different control magnetic field. The mechanical properties of MREs can be divided into two distinctive regimes: the composite properties (with different filler fractions) without applied magnetic field and the composite properties with applied magnetic field. The Einstein-Guth-Gold equation [19] is widely used to approximate the shear modulus of MREs in zero field. In this model, MREs are considered as an elastomer filled with randomly distributed, spherical rigid particles. For the field-responsive behavior of MREs, Jolly *et al.* [18] proposed a quasi-static model to explain the modulus increase by calculating the magnetic interaction between the adjacent particles. Ginder *et al.* [5] and Davis[19] used finite element methods to analyze the modulus increase under varied magnetic fields. Dorfmann *et al.* [13] derived a model represented with the Maxwell’s equation by using the mechanical and thermodynamical balance law. Shen *et al.* [11] developed a model that takes into account the magnetic interactions of dipoles in the same chain and the nonlinear properties of the host composites. Most of models are based on the basis of the dipole model for particle energy interaction, and they have the assumption that the particles are the same size and shape. These models are based on the previous studies on MR fluids and particle chains structure. Their results showed that the field-dependent modulus of MREs varies with the square of the saturation magnetization of the particles. Zhang *et al.* [38] analyzed the complex structure with different size particles or coating particles. The saturation of MREs has also been taken into account. Their theoretical and experimental results indicated that the MREs fabricated with different particle sizes can provide larger field-dependent modulus.

The controllable behavior of MREs is typically characterized by their field dependent modulus. Experiments on double lap shear specimens of MREs were reported in many references [2, 5-11, 17-19]. The change in modulus increases monotonically with increasing volume percentage of iron. However the maximum change in modulus increases to nearly 0.6 MPa as iron volume concentration increases to 30%. The researchers also observed a pronounced drop off in the MR effect and a corresponding increase in field dependent energy dissipation at strains above 1±2%. This strain dependency was attributed to the onset of magnetic yielding of the particle chains.

4. MRE APPLICATIONS

MREs hold promise in enabling simple variable stiffness devices. The pioneering application of MREs was presented in vehicle industry. In US5816587 [39], as shown in Fig. (**1**), a novel method and apparatus for varying the stiffness of a suspension bushing having a MRE disposed therein was presented. This allows for improved customer satisfaction by reducing dissatisfaction associated with braking events, such as shudder, which can result in increased noise, vibration and harshness [40]. It solves these problems by controlling relative displacements of a longi-tudinal suspension member relative to a chassis member in a motor vehicle. The control method is: communicating a brake actuation signal from a brake actuator to a suspension control module; determining from the brake actuation signal a desired suspension bushing stiffness and generating an electrical current in response thereto; and communicating the electrical current to an electrical coil operatively associated with the MRE, thereby generating a magnetic field so as to vary the stiffness characteristics of the MRE in a way to reduce an operator's perception of brake induced shudder. As shown in Fig. (**1**), the apparatus comprises a suspension bushing shaft, an inner steel cylinder annularly surrounding the suspension bushing shaft, a MRE annularly surrounding the annular inner steel cylinder, and an outer steel cylinder annularly surrounding the annular MRE. An annular coil is disposed about an outer peripheral surface portion of the annular inner steel cylinder so as to be interposed between the annular inner steel cylinder and the annular MRE, and the coil is adapted to be electrically connected to the automotive vehicle electrical system by means of suitable electrical leads. By applying suitable predetermined amounts of electrical current to the suspension bushing coil, a variable magnetic field is generated which variably controls the stiffness values of the suspension bushing. The suspension bushings stiffness can therefore be adjusted in response to actuation of the brake system to reduce brake shudder.

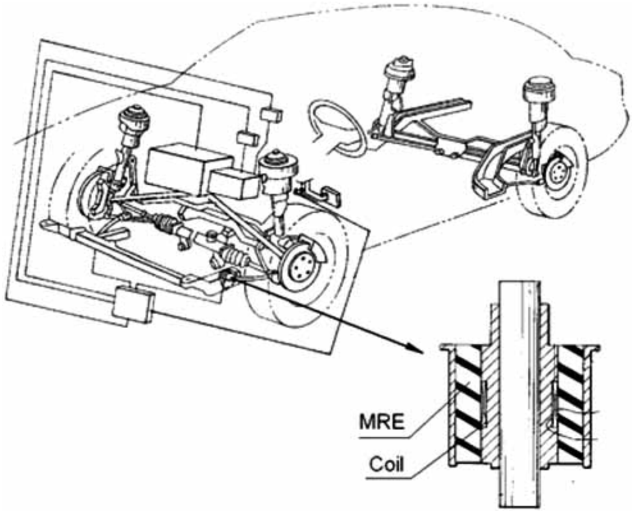

Fig. (1). MREs suspension bushing [39].

The US20036623364 [41] provided a damper assembly to reduce the vibration of a driveline. The driveline assembly is adapted to transmit rotational power from an engine system to a plurality of drive wheels. The damper assembly can be tuned to different frequency to dampen the vibrations of the driveline assembly. The damper assembly comprises an outer housing, an inner housing and a recess defined between the inner housing and the outer housing. A MRE is housed in the recess. The magnetic means are capable of being rotated either towards the inner house or away from the inner house such that the elastic modulus of the MRE is either increased or decreased Fig. (**2**).

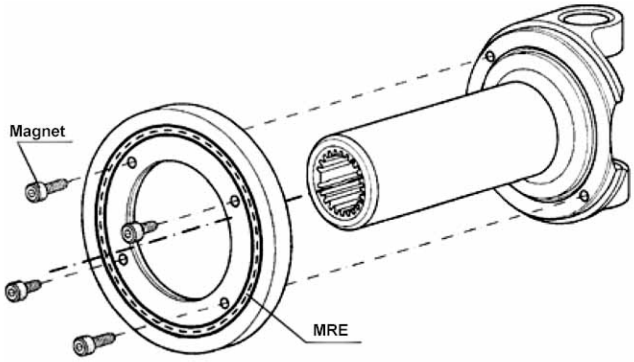

Fig. (2). Driveline having MREs [41].

In US20040126565 [42], a predetermined desired shaped MREs and MREs based device were presented for vehicle usage. The MRE has improved non-linear or variable stiffness. A wire is partially wound around the shaped MREs. The stiffness is variably adjusted over a wide range of values by controlling the magnetic field within the shaped MREs. In applications, these devices can be used in an automotive system; the current can be supplied from the automotive electrical system, electrical current is applied to the wires to generate a variable magnetic field. It is particularly useful for controlling the vibration, or relative displacement, of adjacent components. In certain end use applications, changes in the properties of the MREs based device are, in turn, used to control or adjust the relative displacement of the adjacent structures of the end use application (for example, automobile) in response to preset conditions such as engine speed, vehicle speed and the like.

In US20067086507 and US20050011710 [43, 44], the inventors developed MRE devices and methods for their use for vibration isolation by changing the storage and loss modulii of one or more MRE layers. As shown in Fig. (**3**), the MREs are sandwiched between magnetic activation layers. The magnetic activation layers contain embedded magnetic nodes that control the magnetic field, and thus the stiffness, of the MRE. The current and voltage supplied to the electromagnets will affect the magnetic field strength within the MRE and, hence, the stiffness of the MRE. The current and voltage are determined by the external vibration and associated forces imparted to the MRE device. This system can detect, measure and signal one or more physical manifestations of these external forces, and transform this signal into the appropriate current and voltage to send to the magnets to obtain optimal vibration isolation energy dissipation for a given shock event. These MRE devices are used for vibration isolation of mechanical systems for random shock events.

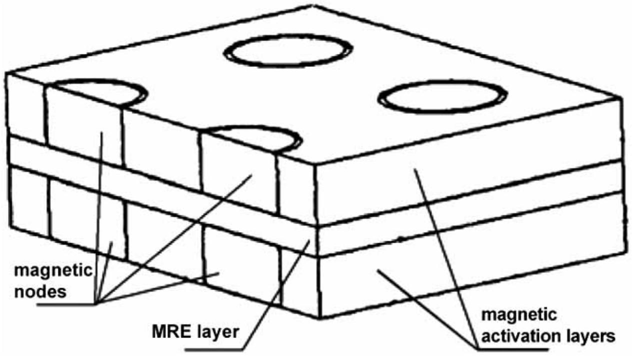

Fig. (3). MRE devices for shock isolation [43, 44].

MREs can also be used as the smart spring in dynamic vibration absorber. In US20067102474 and US20050040922 [45, 28], the inventors presented an adaptive vibration absorbers (AVAs) working with MREs. As shown in Fig. (**4**), the AVA is designed to operate selectively over a range of frequencies rather than a single frequency. It is configured of the elements including a base mass and an absorber mass connected by a pair of MREs, which function effectively as tunable springs and are also held responsible for the advantageous bandwidth increase in vibration suppression by the AVA. The configuration and composition of the elements of the exemplary AVA provide a path (also referred to as magnetic circuit) for magnetic flux that may be induced by a magnetic field source. Specifically, the magnetic circuit passes through MREs. When the source provides the magnetic field and flux travels through the described magnetic circuit, the change of MREs' properties will make the system's natural frequency shift. This change may be controlled as necessary or desired via a control algorithm applied through a processor. A number of researcheres were focused on such applications, for example, Albanese [29] and Holdhusen [40] presented MREs absorbers working on a compress mode and Deng [46] presented a MREs absorber working on a shear mode. Their results indicated that the frequency of vibration absorber can be tuned in a wide frequency range, and the controlled frequency band was expanded too.

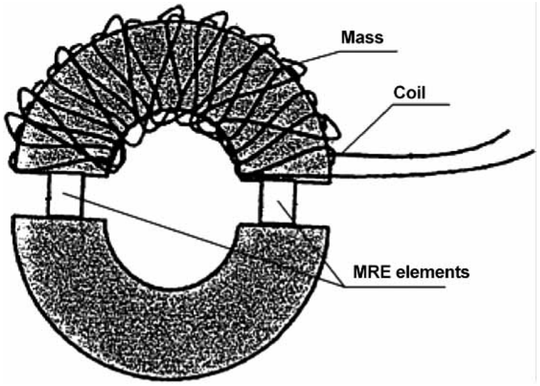

Fig. (4). AVA having MRE elements [45, 28].

MREs' controllable stiffness can also be used in many other industrial applications. In US20036544156 and US20010015141 [47, 48], researchers introduced a MRE based roller for papermaking machine. The intrinsic mechanical properties of a roll cover are altered by using an external stimulus such that nip pressure (for example, on a paper web) can be controlled in inches wide or less zones across the width of the nip. Such roll cover alterations may take place in the press section, the size press and coater, and in the calender (hot-soft, gloss, super-calender, and the like). The roll cover can be impregnated with MREs which alter either the density or the effective modulus of the cover when exposed to an external or internal stimulus such as an electric or magnetic field. This allows the user the ability to make the roll cover either harder or softer relative to its nominal (baseline) hardness. The stimulus itself is controlled in the cross-machine direction in a manner resulting in pressure control of the cover properties [47, 48].

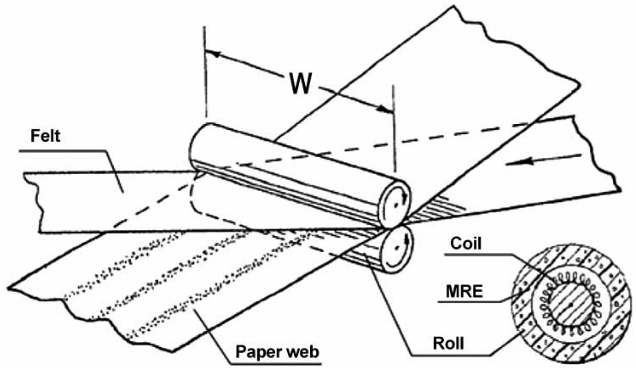

Fig. (5). The MRE roll of papermaking machine [47, 48].

In US20046681849 and US20030037921 [49, 50], inventors provided packers and bridgeplugs having a MRE for the annulus or bore sealing element. Packer seal elements are fabricated with MR elastomers or foams for disposition about an electromagnetic field winding embedded within and around a packer or bridgeplug mandrel for positioning downhole, the mandrel winding is de-energized. When positioned, the mandrel winding remains de-energized when the elastomer sealing elements are expanded to sealing engagement with the well bore or casing walls. After sealing, the mandrel windings are energized to stiffen the elastomer elements in the position and shape the elements were given while de-energized.

One other application was introduced by US20056877193, US20060168780 and US20040074066 [51-53]. As shown in Fig. (**6**), it is a releasable fastener system that provides for a controlled release or separation of a joint in a shear and/or pull-off direction, while providing active or variable damping properties when the fastener is engaged. A releasable fastener system comprises a loop portion comprising a support and a loop material disposed on a surface thereon; a hook portion comprising a support and a plurality of hook elements disposed on a surface, wherein the plurality of hook elements comprises a MRE adapted to change a shape orientation and/or flexural modulus of the hook elements upon receipt of a magnetic signal; and an activation device coupled to the plurality of hook elements, the activation device being operable to selectively provide the magnetic signal to the hook elements and effectuate a change in the shape orientation and/or flexural modulus of the hook elements to reduce or increase a shear force and/or a pull-off force, and wherein the change in the flexural modulus of the hook elements provides a damping capability to the fastener system.

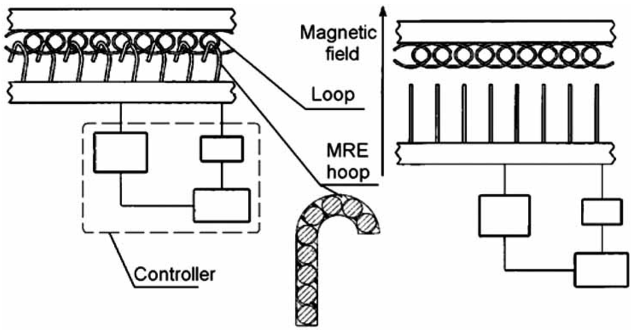

Fig. (6). Releasable fastener system based MREs [51-53].

Because of their magnetic field sensitive behavior, MREs were also considered as one of ideal materials for sensor and actuator. In US Patent 5814999 [54], a method and apparatus for measuring displacement and force applied to an elastomeric body having a MRE disposed therein has been discovered. A transducer apparatus comprises two structural members and a MRE interposed between them. A module is provided for acquiring measurement data by applying a drive signal to an electrode disposed within the MRE and monitoring a preselected electrical state of the MRE. The module generates an output signal corresponding to variations the preselected electrical state caused by deflections of the MRE. It increases the usefulness of conventional elastomeric members by providing within them additional materials so that they may serve as transducers in addition to serving as isolators and pivotable joints, etc. This combination of functionality reduces part and assembly complexity as well as improving overall package efficiency for the assembled product.

5. CURRENT & FUTURE DEVELOPMENTS

In MR material family which consists of MR fluids, MR foams and MR elastomers MR elastomers exhibit unique characteristic that their modulus can be controlled by an external magnetic field. However, compared with MR fluids, MR elastomers have only found limited applications. One major reason for this is that the field-dependent modulus change is not wide enough. In other words, current MR elastomers haven't high enough MR effects to meet with many applications. Thus, to greatly enhance the applications of MR elastomers, the material development is the first priority. Fortunately, a number of groups have taken efforts to develop high-efficiency MR elastomers. Gong *et al.* [55] reported a silicone rubber based MR elastomers, the MR effect of which was as high as 878%. They also fabricated and tested natural rubber based MR elastomers, with a relatively low MR effect of 133%. The results imply that the matrix plays an important role in enhancing MR effect. However, the mechanism on the greatly enhanced MR effect has not reported yet. Also, further commercialization and application of such materials sound to need further study. Similar to other new material technology study, the fabrication of stable MR elastomers with enhanced MR effects needs great efforts and collaboration of researchers from different disciplines.

Besides material development, the working modes or mechanisms of MR elastomers contribution to practical applications are also crucial in developing high-efficiency MR elastomer devices. The development of MR elastomer vibration absorbers has attracted growing interest [46, 56]. Researchers studied MR ealstomer based vibration absorber performances under three working modes, including shear, longitudinal and squeeze modes [56]. Their results demonstrated that MR elastomer absorber working in squeeze mode exhibited the largest frequency shift of 507%. This research also demonstrates that appropriate design configurations would be helpful to develop high performance MRE devices. In addition, the appropriate control strategy will also be needed to match the application of MR elastomer as semi-active vibration absorber.

In summary, MR elastomers, as important intelligent or functional materials, have many applications prospect, which provide an impetus for continued research in this area. Numerous applications, which make use of controllable stiffness and the unique anisotropic characteristics of these elastomers, will be developed and the research efforts of the past decade in MREs will be paid off in the near future.

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