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A review on magnetorheological elastomers

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Abstract. Magnetorheological Elastomers (MREs) are a type of magnetorheological (MR) material, which is a combination of magnetic particles and a soft elastic matrix. As a new class of intelligent material, MREs possess controllability, reversibility, rapid response as well as stability under magnetic fields. Thanks to these characteristics, MREs have found a wide range of applications in many fields, such as vibration absorbers, absorber isolation, pumps, and soft robots in recent years. All these applications will be discussed in this review. Additionally, this paper will describe the effects of particles, matrices, additives, and synthesis on the performance of MREs.

Keywords: magnetorheological elastomer, magnetic particles, matrix, absorber vibration.

1. Introduction

Smart or intelligent material is defined as a material susceptible to respond to external stimuli and hold reversibility and controllability.[1-4] Traceback to the beginning of mankind, materials science experiences a range of evolution: from the application of inert materials, to active or adaptive materials, and eventually to intelligent materials.[1] Intelligent materials can be classified into piezoelectric materials, shape-memory materials, chromoactive materials, photoactive materials, magnetorheological materials (MR), and so on.[2] Magnetorheological (MR) materials consist of magnetic particles loaded in a soft non-magnetic matrix, which provide some interesting phenomena such as the MR effect, magnetostriction effect, magneto-deformation effect and magneto-mechanical effect, and so on.[3] In the matrix aspect, MR materials appear in various forms such as MR fluid (MRF), MR elastomer (MRE), MR foam, MR grease (MRG), MR polymer gel (MRPG), and MR plastomer (MRP).[3] MRF is the first type of MR materials and it has vast applications in many fields due to its low viscosity and fast changes in rheological properties. In 1948, Jacob Rabinow introduced a series of studies about MR materials and demonstrated MR effect using MRF.[4] MRF shows reversible, instantaneous, and large stress enhancement in a magnetic field. Today, MRFs are widely used in engineering and provide plenty of meaningful applications like vibration absorbers/isolators, polishing devices, clutches, dampers, and valves.[5,6] However, MRFs exist some fatal drawbacks, such as sedimentation of magnetic particles and limitations in MRF containers.[6] The main reason is the wide gap in high density between fluid and particles and mobile fluid. To figure out the aforementioned problems, scholars started to attempt using solid matrices to replace fluid matrices. Meanwhile, rich types of solid MR materials are developed such as MREs, MR foams, MRPs, and MRPs.[3]

Among all of them, MREs dramatically fire the high curiosity of scholars so that they pay more attention to this. MREs have been regarded as the solid analog MRF, which are composed of micro-size magnetic particles embedded in a soft and solid non-magnetic matrix.[7-9] The problems of MRF such as particles settling, leakage of MRFs, and sealing can be addressed easily through the replacement of fluid matrices with solid matrices. However, when the matrix is curing and polarized particles are embedded in the rubber-like solid materials, the arrangement of polarized particles cannot be changed under a magnetic field, which is essentially different from MRF. Therefore, MRF is always used in extreme deformation conditions and MRE should be checked whether or not the matrix is destructive. In 1983, Rigbi and Jilken reported the MRE.[7] After 13 years, Jolly and his colleagues began to explore the properties of MRE.[8] Finally, their team found numerous fundamental and essential theories of MRE like the arrangement of MRE, particle line formation, and shear modulus model.[9]

In this review, MREs are presented and discussed on all-sided. The review is organized as follows. The materials and syntheses of MREs are demonstrated in § 2. In § 3, current applications

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development is discussed from relatively advanced products industry to mature leading-edge products. In § 4, we summarize MREs and show the present outlook and future expectations of MREs.

2. Materials and syntheses of MRE

Generally, the MRE materials are composed of magnetic particles, additives and a non-magnetic elastomeric matrix, as shown in Fig. 1. All these components could dramatically affect the properties of MREs. We will discuss them one by one below.

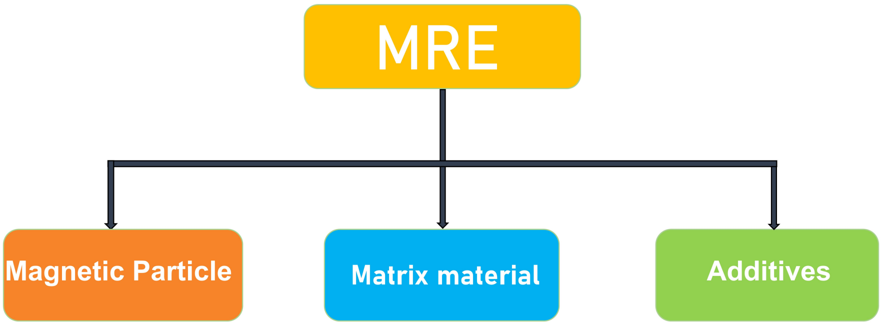

Fig. 1. Main constituents of MREs

2.1 Particle

Magnetic particle plays an essential role in the MR effect. Generally, scientists and Engineers would like to use magnetic particles with high saturation magnetization and short-term inter-particle attraction. Carbonyl iron particles (ClPs) produced by thermal decomposition of iron pentacarbonyl is the most studied and used MR particle. [10,11] Davius utilizes finite element method to analyze the magnetization of particles, and numerically finds the highest MRE effect could be obtained when the volume fraction of particles in materials is 27%.[12] Fuchs *et al* use the atom transfer radical polymerization technique and plenty of machines to investigate the methods, reducing iron particles oxidation.[13] Finally, their group discovered MREs which cover a layer of iron particles in the surface have a higher oxidation stability. In this study, Behrooz *et al* chose fabricated MRE with polymerized and regular iron particles as samples, exploring the possibility and extent of oxidation resistance, shear modulus, and stiffness change due to an applied magnetics.[14] The results show that elastomer matrix can reduce the shear modulus significantly, the loss of shear modulus can be reduced by covering iron particles. Małecki *et al* investigate the factors of encapsulating CIPs cover different types of silica on the properties of MREs under a 430 mT magnetic field.[15] The results show that various particle coating is the main reason for the different magneto-mechanical responses of the MREs. Dong and his team conclude from their tests that the loss factor of the MRE which joined with altered CIPs diminished particularly, and the tensile strength of such materials has been much moved forward.[16] Meanwhile, the MR effect of MRE also kept great. Vaganov *et al* proposed a Stoner-Wolfas model for single-domain particles to explain the nature of the magnetization profile of heterogeneous magnetorheological polymers filled with NdFeB particles.[17] By setting different parameters, it was found that the particles may have large angular rotational amplitudes during the magnetization process. The measured hysteresis loops on magnetorheological samples filled with spherical NdFeB particles were compared qualitatively, producing hysteresis loops that decrease with increasing matrix compliance. In this investigation of Zhou's group, utilizing bio-inspired dopamine modification to improve the cover of CIPs function in which get better mechanical properties and MR effect in MREs.[18] Additionally, MRE composites filled with polydopamine (PDA)-coated CIPs have a high magnetic field-induced storage module when reaching magnetization saturation. the relative and absolute MR effects of the MREs reach 294% and 0.68 ± 0.002 MPa, respectively. Ardehali *et al* made a study of the viscoelastic properties of a

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hard magnetic particle-based MRE with a volume fraction of 15% NdFeB magnetic particles under an applied magnetic field.[19] The loss modulus was almost independent of the shear strain amplitude and the applied magnetic field at different magnetic field levels from 20.2 to 1.0t. Finally, a phenomenological model to predict the variation of storage and loss moduli of hard magnetic particle-based MRE at different excitation frequencies and flux densities is presented and it is confirmed that this model can accurately predict the viscoelastic behavior of hard magnetic particle-based MRE under various operating conditions. In the Xie group's study, a more pronounced bi-directional control effect was achieved by incorporating pre-magnetized hard magnetic NdFeB particles into the silicone rubber.[20] In addition, the surface magnetic field strength of the MRE was measured and the internal structure was observed. It was concluded that the MRE has the highest surface magnetic field strength and a wide range of variation in storage modulus, loss modulus, and corresponding magnetic field control. Zainudin *et al* uses cobalt particles with dual, special magnetic, and electrical properties as a filler in MRE.[21] They prepare three kinds of anisotropic MREs which contain 53%, 60%, 67% of cobalt particles. The effect of cobalt on the electrical properties was analyzed and the forces acting on the three MREs were compared. The experiments ultimately show that higher cobalt content favors higher MR effect and lower resistivity. The use of cobalt as a filler may therefore be a potential candidate for force sensors.

2.2 Matrix

Matrix materials have obvious influences on the properties of MREs, such as MR effect, initial modulus, filed-depend modulus, and so on. Many soft and hard materials have been applied for the fabrication of MREs.

Silicone rubbers, as the most widely applied materials in MREs, as both organic and inorganic properties. These properties are mainly attributed to Si-O bonding and allow more superior heat resistance, electrical insulation, and chemical stability.[22] Besides, the easy fabrication procedure is also another important reason for wide application of silicone rubbers in MREs.[23]

Generally, silicones are resin in the liquid state, promoting a homogenous distribution of magnetic particles under simple stir and relatively well suspension of the particles during the curing process.[24] Besides, inherent low viscosities of silicones allow the flexible locomotion of the magnetizable particles under magnetic field when the anisotropic MREs are required. Koo utilizes high-strength silicone rubber as the binding agent and obtains MRE with both amazing stiffness and flexibility.[25] Li fabricates silicone-rubber-based MREs with various weight fractions of magnetic particles, and utilizes a low vacuum scanning electric microscope to observe the microstructures of MREs.[26] The results show that iron particles disperse randomly in the isotropic MREs. Yarra *et al* investigated the large strain behavior of natural rubber and silicon-based MRE under the influence of structural vibration relief.[27] Different anisotropic silica-based and isotropic natural rubber-based MREs were prepared and the mechanical properties of the samples were investigated using a special electromagnetic double-lap shear experimental setup. It was observed that isotropic natural rubber-based MRE exhibit high MR effects under combined axial and shear loading and may be suitable for applications with high demand forces. Besides real-world experiments, some simulations are also performed based on silicone rubber matrix. Xu applies the finite element method to investigate the locomotion of two particles in silicone rubber matrices, and the influencing factor on the corresponding locomotion, including particle distribution angles, applied magnetic field strength, particle radii, and distance between particles.[28] The last factor extensively affects the contact time of magnetic particles and then has an obvious influence on the chain formation of magnetic particles in the MRE, which most drastically affects the locomotion of magnetic particles. Clark presents an ultrasoft PDMS-based MREs to meet the requirements of magnetic field-dependent mechanical tunability in biological applications, especially in the imitation of dynamic changes in the extracellular matrix for a wide range of biological systems.[29]

Natural rubbers, as one of the oldest materials from nature, have been utilized by human beings for nearly 3000 years.[30] It is a versatile material widely applied in engineering due to its good

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impact resistance. Besides, in dynamic or static engineering applications, the requirements of high tensile strength, high tear strength, and outstanding fatigue resistance could be easily met under the application of natural rubbers.[31] In Yoon's team, MRE specimens are allowed to cure in an anisotropic mold that was used to induce the magnetic field by using natural rubber which gives better mechanical properties than other rubbers, and CIP was selected to generate modulus in MREs in relation to the magnetic field.[32] Moreover, an evaluation system incorporating a magnetic flux generator (MFG) was designed, a system that determines the variation in shear modulus. The experimental reports obtained a maximum variation in shear modulus of 76.3% with 40 vol% and an induced current of 4 A. Capitalising on these values, the suitable CIP volume fractions and induced currents can be used as guidelines for fabrication designs with NR as the basis. Khimi and Pickering discuss the impact of existing antivibration rubbers on the dynamics properties of magnetorheological elastomers.[33] In this research, natural rubber is the base for isotropic and anisotropic MREs, and silane-modified iron sand was prepared that shows the coupling between natural rubber and iron sand. It is found that the trends of energy absorption at around Tg can be reversed due to rubber chains segmented move, and energy absorption is the main influence.

Ethylene propylene diene monomer (EPDM) rubbers have been extensively applied in outdoor engineering for many years, due to the advantages of good vandalism resistance, light-weight, and better contamination performance. Plachy *et al.* fabricate MRE based on EPDM rubber matrix.[34] An azodicarbonamide-based foaming agent was used to control its porous properties and magneto-mechanical behavior. They found that the porous system displayed a lower mechanical hysteresis in single strain measurements. The main reason is that pores increase the distance between particles, further resulting in lower strength of the magnetic network. The ageing of filled and cross-linked EPDM has been studied by Tomer *et al.* for different time intervals under accelerated UV irradiation at 60℃, thermal ageing at 100℃ and in nitric acid vapors.[35] Tomer *et al.* measures their hardness and found that the filled cross-linked EPDM rubber shows a rapid increase in hardness values after exposure to nitric acid vapour without any induction period. Furthermore, the development of functional groups is monitored by ATR spectroscopy and the oxidation reaction after various types of aging increases with increasing exposure time.

2.3 Additives

Additives are the additional components of MREs to enhance the MR effect. Carbon black (CB) is the first carbon-based additive that has been reported for improving the electrical conductivity of MREs.[36] In Wang's research, the interaction effects, MR effect, and mechanical properties were investigated between iron particles and silicon rubber.[37] The observation concludes that if interaction increases, the strength increases. In addition, the structure of silane coupling agents decreases the MR effect due to the uniform dispersion of iron particles making the size of iron particles smaller. The magnetorheological composites reinforced with multi-walled carbon nanotubes (MWNTS) make full use of the intelligent technology and excellent properties of MWNTS. In Sun's study, it displays a range of MR nanocomposites benefits like damping, higher zero-field stiffness, and absolute MR effect induced at the higher magnetic field.[38] Graphene is also widely applied as an additive for MREs. Li *et al* prepare a series of MREs based on graphene nanoplatelets, improving adhesion forces and magneto-sensitive adhesion properties.[39] In this research, the adhesion forces of MREs keep the same. Research results displayed that the adhesion of modified MREs increases by 359.4% with the increase of GNPs mass fraction from 0 to 1.5%. With the increase of the applied magnetic field, the adhesion of the modified MREs increases. When the magnetic field ranges from 0 to 300mT, the adhesion of the sample containing 15 Vol% ferromagnetic particles increases by 65.6%. Other additives are also reported.

The damping and mechanical properties of MREs are affected by the interface interaction between the CIPs and the elastomeric matrix. Based on this point of view, Gao and his group prepared a high-performance MRE based on ethylene/acrylic elastomer with calcium carbonate as a kind of compatibilizer, while experimentally observing this type of MRE.[40] The experiments

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ultimately show that the tensile strength increases when calcium carbonate is filled with MREs. In addition, the magnetically induced properties of the MREs are enhanced by the transfer of stress between non-magnetic particles.

2.4 Syntheses

Typically, the manufacture of MREs includes three main steps: feeding, mixture, and curing, as shown in Fig. 2. As mentioned before, silicone rubber is liquid before curing as the most widely adopted matrix.[41,42] Hence, the first step for the fabrication of MRE is dispersing magnetic particles as well as additives including carbon black, graphene, and other additives in liquid silicone rubber. Then the raw materials are mixed with mechanical mixers or ultrasonic mixers. Finally, the mixture is poured into a mold and cured. During the curing procedure, an external magnetic could be applied to obtain anisotropic MRE. At the beginning of the curing process, the substrate remains in the liquid state and the magnetic particles are configured in the same direction as the magnetic field. After complete curing in the mold, the magnetic particles are trapped in the polymer network. In case of no applied magnetic field during the curing process, the magnetic particles are randomly distributed, resulting in an isotropic MRE after curing. Besides the conventional fabrication method, some novel methods, such as 3D printing is also investigated by researchers.[43,44] Approaches to the preparation of anisotropic and isotropic MREs.

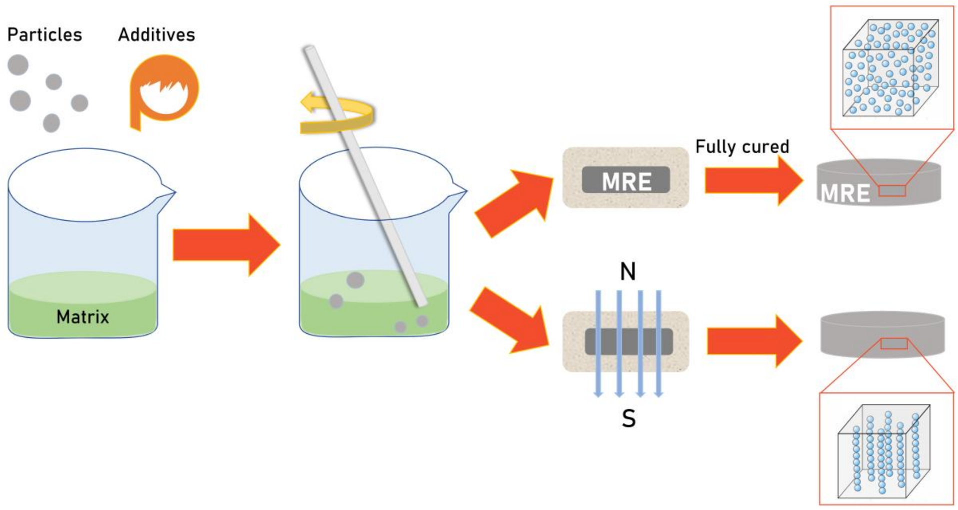

Fig. 2. Approaches to the preparation of anisotropic and isotropic MREs.

3. Current application

3.1 Absorber vibration

Vibration absorbers are an effective way to passively control vibration. The stiffness and mass of the absorbers are expected to match with "anti-resonance" in the total system response. However, traditional vibration absorbers are only effective within a narrow working frequency range. Thanks to the unique characteristics of MREs whose modulus is capable of being adjusted through an external magnetic field.[45,46] Deng *et al* concentrate on improving an adaptively tuned vibration absorber (ATVA) based on the distinct properties of MREs, which modulus is controllable in the magnetic field.[47] The results of the experiment exhibit that the natural frequency of ATVA can be adjusted to range from 55Hz to 82Hz. Moreover, it proves in the experiment that ATVA invented possesses high absorption capacity, achieving 60 dB. In Hoang and his colleagues' study, a conceptual ATVA with soft MREs is proposed for damping vehicle power systems.[48] The MRE material composite in this application by rubbery silicone polymer matrix and a ferrous filler, with a

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volume ratio of 27.6%. The benefits of ATVA were shown that the vibration of the powertrain was suppressed effectively as applied this type of MRE material, it is more suitable for damping of power system making the comparison with conventional. Later a few years, Hoang and his colleagues get further research.[49] They deduce the formulas of storage modulus and loss factor to be explicit functions of applied magnetic field density which help the design of ATVA. Hence, the ATVA frequency can be tuned appropriately to the excitation frequency. The natural frequencies of the powertrain can be actively tuned and avoid the resonant area of excitation frequency though utilizing ATVA based on MRE. Therefore, ATVA reduces powertrain vibration significantly. Yang *et a*l study presents a shear mode semi-active dynamic vibration absorber based on MRE.[50] The structure of the new damper is designed and the frequency shift characteristics are analyzed theoretically. A semi-active damper that is effective for axial vibration control of the shaft system is proposed. The experimental results indicate that the designed axial semi-active dynamic damper outperforms the conventional passive dynamic damper in terms of frequency shift characteristics and vibration absorption capacity. In Sun's group research, they design a kind of ATVA based on a multilayered MRE and prototype.[51] To show the benefits of a multilayered MRE absorber clearly, an experiment is being that makes a comparison with two kinds of MRE absorbers that only have a single layer. The vertical support capability and the tuning frequency range are taken into account that found the difference between the two kinds of ATVAs. These show the larger oscillator stroke and lower working frequencies that multilayered MRE absorbers have. The result demonstrated that it is difficult for ATVA with single layer MRE, while the frequency of ATVA with multilayered MRE absorber could be lower than 10 Hz. Moreover, ATVA is more useful than a passive absorber over a wide frequency range. Shortly afterward the sun's group further investigated the lateral flexibility and effective frequency range of the absorber to be improved by the use of the laminated MRE structure and the hybrid magnetic system.[52] Absorbers that have the integration of the self-sensing capability could be operated without sensors. Therefore, a series of experiments were carried out to check the self-sensing capability of the absorber by measuring the frequency shift characteristics and evaluating whether it was effective for vibration damping. The experimental consequences produced that the absorber's natural frequency can be changed from 8.5Hz at 0A to 4.8Hz and 11.3Hz at 3A, the frequency of the self-sensing voltage is equal to the excitation frequency. Moreover, the experiments verify the vibration control effect of the self-measured MRE absorber, which is more effective than the passive absorber for damping. Later, Sun led his team to design a new type of MRE absorber. This new absorber uses an eccentric mass on top of the multi-layer MRE structure.[53] The use of the eccentric mass allows the new absorber to have not only the traditional translational vibration mode but also adds a new vibration mode, the torsional vibration mode. The new absorber was tested on a horizontal shaker table and it was found that the MRE absorber achieves double natural frequencies, with double natural frequencies of vibration modes increasing as the applied current increases. In addition, the effect of inertia on the dynamic performance of the absorber was also investigated in order to demonstrate that the design of the new MRE absorber was effective and feasible. A final experiment, the vibration absorption experiment, demonstrates the usefulness of double natural frequencies for absorbing vibration energy. Meanwhile, it show the potential of the new MRE absorber to extend the effective frequency range. Sun's group began to design and invent a kind of innovated hybrid nonlinear MRE with the advantages of a nonlinear force – displacement relationship and variable stiffness technology.[54] In order to verify the merits of the proposed absorber, two pairs of magnets are moved at a rotational angle to each other, and the adaptability of the hybrid absorber is verified from observations and calculations, where the intrinsic frequency of the device increases as the magnetic field of the MRE layer increases; in experiments, the non-linear MRE absorber exhibits a more bounded effective bandwidth than the linear absorber with constant current conditions. Similarly, the Sun's group evaluated the vibration absorption performance of the non-linear MRE absorber and concluded that the non-linear MRE absorber outperformed other absorbers in terms of vibration damping performance. Thus, an adaptive broadband damper was designed and validated. The Chen's group

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has taken advantage of the excellent magnetically controlled stiffness properties of MREs as spring elements for dampers to carry out experiments.[55] In this experiment the mechanical strength and loss factor of the MRE were improved and reduced, separately, by interface modification. The CIP surface was modified using the sol-gel method. The dynamic mechanical properties of the MRE samples of the modified CIP were measured and analysed using scanning electron microscopy and Fourier transform infrared spectroscopy. The analysis showed that the modified CIP with a silica-covered surface resulted in improved miscibility, allowing for better bonding of the particles to the matrix, and a much higher tensile strength of the material. Jang's team was concerned with ease of installation in the factory and focused on the environmental robustness, large size, high power consumption and complex installation on the actual factory, consisting of a solenoid and MRE tunable vibration absorber (TVA).[56] This led to the design of an all-in-one module using MRE's TVA. The TVA module was designed so that the existing target system could be easily connected. Experiments have shown that 94% stiffness variation and 58% vibration suppression can be provided over a frequency range of 51.6 - 71.9 Hz. The design allows an embedded controller to be mounted within the TVA module and the sensors to be replaced with MRE self-sensing.

3.2 Absorter isolation

Vibration isolators are capable of isolating an object or equipment from the source of vibrations.[57,58] Through the application of MREs, the mechanical properties can be tuned in real-time via an external magnetic field. Zhu et al investigated both experimental and modeling studies of the magnetic field-induced viscoelastic properties of MRE act under different loading cases conditions.[59] The loss factor and the experimentally determined shear storage modulus are obtained from the characteristics of the dynamic properties of the MRE devices. Therefore, it shows that the MREs possess damping properties and variable stiffness. Yang's team developed and manufactured a new, multi-layer MRE isolator with hybrid magnets.[60] It has a stiffness that decreases with increasing applied current. It can also be used as a conventional MRE isolator, where the effective stiffness and intrinsic frequency increase when negative current is applied. It was also tested how effectively the device could reduce vibration. With the switching control logic, there was a significant reduction in vibration in the main system. This confirms that the design of the novel MRE isolator is successful. Xu *et al* designed multi-layered two- and three-component MRE isolators using a one-dimensional phonon crystal model.[61] The transmission and reflection of the elastic waveband structure were investigated by the transfer matrix method. It is found that the modulation of the external magnetic field affects the position of the elastic band gap (EBG) and that changing the component thickness can modulate the width of the EBG. Lu *et al* investigated the vibration control of platform structures by utilizing MRE isolators, designing a new MRE isolator base on the single-degree-of- freedom (SDOF) dynamic model and the multiple-degree-of-freedom (MDOF) dynamic model of the platform system.[62] In order to address the shortcomings of the conventional switching control law, an improved semi-active variable stiffness (SAVS) control law utilizes the continuous variable stiffness of the MREs. The results show that the improved SAVS control law has better vibration control compared to the switching control law. For the MDOF platform, a simplified control method that combines the local response signal with an equivalent SDOF representation to generate control parameters for a single isolator is proposed. Numerical simulation analysis shows that controlling the vertical displacement works better than controlling the rotational displacement of the platform. This indicates the need for further improvement of the control effect MDOF system response at different control points in the future. In Zhao's group, a transversely laminated MRE isolator was developed and fabricated based on MRE controllable and field-dependent properties.[63] A set of dynamic tests were carried out to analyze the change in effective stiffness and equivalent damping. The maximum increase in effective stiffness was 114.12% when the current was increased from 0 A to 3A. Thus, the laminated MRE isolator can be further developed in the field of vibration suppression in bridge monitoring equipment. Yarra *et al* designed a large-scale MRE-based vibration isolator for highway bridges.[64] The effect of magnetic

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field, strain level and loading frequency on the effective stiffness of the bearing is investigated. The experimental results show that an increase in the applied magnetic field leads to an increase in the effective stiffness of the adaptive bridge bearing and the apparent shear stiffness due to compression forces. Furthermore, the apparent shear stiffness increases with increasing loading frequency, while the compression force leads to a smaller MR effect. Susheelkumar and his colleagues investigated the preparation and dynamic characteristics of polymer-based MREs for vibration isolators.[65] Experiments were carried out at different magnetic fields, strain amplitudes and frequencies to find the frequency of movement of the MRE isolators. The experimental results show that changes in frequency, strain amplitude and magnetic field cause the shear module of the MRE to change together with the loss factor. A shift frequency of 6 Hz from 30 Hz to 36 Hz is more effective in reducing the vibration amplitude compared to a passive isolator. Jalali *et al* invent a new bi-directional shear mode MRE vibration isolator.[66] In shear mode, simultaneous vertical and horizontal operation was achieved and the maximum MR effect in vertical and horizontal shear modes was 35% and 27% respectively. In addition, a basic mathematical model of a single degree of freedom system was developed. The intrinsic frequency shift of the magnetic flux density of the MRE separator was found to be 6.1% at an excitation frequency of 1HZ, which demonstrates its potential for vibration control applications.

3.3 Pump

Pumps especially micropumps are widely applied in microfluidic flow control.[67,68] MRE materials could be utilized for these pumps with simple structures and separated power supply. Behrooz *et al* propose a flexible magnetically driven microfluidic transport system using isotropic MREs.[69] By modelling a two-dimensional model, it was concluded that a soft MRE membrane could be made into a flexible microchannel. Furthermore, after analysing the resulting data, it was found that the system would have the ability to drive the fluid with the appropriate parameters which mainly involve the channel diameter, the elastic modulus of the channel, the elastic base constant and the applied magnetic load. A few months later, Behrooz's team started a three-dimensional simulation of a controlled flexible magnetically activated micropump, starting from the point that tubular micropumps use magneto-induced deformation of MRE and unidirectional flexible tapered valves for fluid transport.[70] As with the previous research approach, a model a different three-dimensional model of a controlled unidirectional flexible magnetically-actuated fluid transport system is also proposed and experimental data are analysed for it. Similarities and differences between 2D and 3D can be found in the experimental results. The channel diameter, valve spacing, microchannel elastic modulus, magnetic loading and magnetic permeability of the soft MRE membrane have similar effects in the 2D and 3D analysis. However, the valve length and valve opening distance, elastic base constant and fluid viscosity show a different behaviour to the 2D model. Ehsani and Nejat have invented an electromagnetically driven micropump with a flexible valve sequence by exploiting the rectification mechanism of lymphatic vessels in lymphatic transport systems by placing two flexible valves within the microchannel.[71] In this micropump, valve performance is the main factor affecting the transported fluid, so the pair conducted simulation experiments on this factor and investigated the effect of key geometrical, magnetic and structural parameters on the net transport volume through extensive parametric studies. Ultimately, an optimal model was produced which was able to pump 0.055 (μl) of water in 1 second (at 25°C), nearly twice as much as the basic design. Tahmasebipour *et al* propose a bidirectional electromagnetic micropump to address the control of recovery time of nanocomposite magnetic membranes.[72] A better balance between supply and pump modes is created by a secondary magnetic field, in other words, switching the magnetic field between the two coils so that the membrane response and recovery time are in equilibrium. This results in a maximum flow rate of 1.25μl min-1 when the system is operated at 0.1Hz. Cao *et al* used a 3D printing-assisted method to compose a magnetically powered pulsation pump (MAPP) containing a flexible check valve and a magnetic source tube.[73] The liquid was pumped through the check valve by generating high driving

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pressure. Therefore, MAPP can be used in the development of intelligent pulse pumps and their use in microfluidics, heart pump components, etc. A series of studies have been carried out by Ehrlich *et al* on this aspect and also from the fact that the actuation capacity under magnetic field action can have different deformation patterns, the degree of deformation being determined by the magnetic field strength and it gradient.[74] The MRE body deforms due to the attraction of the magnetic circuit that can act from one side. MRE materials can be used in linear actuators for applications such as tactile feedback and pumps. However, if the magnetic field is oriented, the ring-shaped MRE bodies can also be deformed radially around its cylindrical axis. The opening of this unusual type of deformation is controlled by the strength of the magnetic field and so a proportional valve can be formed. Zhang and his team simplified the fabrication process of the MRE by designing a stand-alone microfluidic device that allows a micropump, micromixer and microvalve to be integrated into a single PMMA chip.[75] The use of the microcontroller and sensor gives a highly controllable miniaturised platform driven by a rotating magnet rotor and a precise valve system.This MRE chip embodies great potential, not only for practical applications in biological and chemical analysis but also for highly customized testing or evaluation due to the low manufacturing costs and modularity of the microactuator.

3.4 Soft robot

Soft robots with mechanical functioning relying on the application of deformable structures to mimic the biological world and organic materials is a cutting-edge technology, showing great potential on bioengineering, mechanical engineering, pharmaceutical engineering, micro sensors, minimally invasive surgery. MRE soft robot could be controlled by magnetic fields with favourable bio-compatibility and the ability of remote control. In the investment of Diller *et al* invent a swimming robot applied in untethered motion at mid to low Reynolds numbers. The motion of the robot is generated by continuous travelling wave deformation, utilizing a continuous magnetization profile and a flexible body.[76] Diller et al demonstrated control of the first distributed magnetization profile used to induce continuous deformation and drive a swimmer at a low Reynolds number, and measured deformation and velocity as a function of magnetic field strength and frequency, finding a linear relationship between deformation amplitude and drive field strength. The swimming speed of the robot was compared with other models, which confirms the unlimited potential of the robot to reduce its size to the micron level for medical, bioengineering, and other applications. Rigid robots have difficulty overcoming obstacles and changes in texture or material in unstructured environments. In Sitti's group, the high mobility of a magnetoelastic soft millimeter-scale soft robot is demonstrated through multimodal motion and a theoretical model is used to explain the formation of the robot's locomotion patterns.[77] The movement patterns of the soft robots are divided into eight main categories: swimming, meniscus climbing, landing, immersing, rolling, walking, crawling, and jumping. in addition, they can perform tasks such as picking up and placing goods like a delivery man. Sitti’s group proposes another jellyfish-like micro-robot.[78] The robot's magnetic composite elastomeric suspension bar can have multiple functions at moderate Reynolds numbers. Furthermore, the interaction between fluid flows resulting from the robot's body movements is used to perform different predation-inspired object manipulation tasks. This gives an improved aspect to other robots with jellyfish-like structures. In Signor's Group research, a magnetic sensor, which would otherwise only work in a three-dimensional magnetic field, was made to operate without the influence of stray magnetic fields as well. This sensor applies multiple magnetic pixels that operate at the right magnetic field gradient. The chip brings together the pixels and the conditioning electronics. The contribution of force output is limited to 0.3% of the full scale under a 2-mT magnetic field stray field. This is an enhancement of two degrees of magnitude compared to existing techniques. In addition to this, the 3D magnetic sensor is now demonstrated to be robust to real-world parasitic stray fields. The poor independence and stability, as well as the vulnerability of conventional soft robots, attracted the exploration of zheng *et al* In their research, a new drive system was proposed, the Electro-Permanent MRE (EPM-MRE), which uses non-contact

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magnetism to enhance the independence and stability of soft drive systems. This system was tried out in a robot gripper to explore the mechanical principles and parameters of the design. In the process, an EPM-MRE drive suction cup was built and it was eventually found that this system could be used to build a stand-alone, relatively flexible soft robot. Bira and his group propose the use of multifunctional materials to improve the grip strength of the machine. This is due to the increased grip strength of magnetic particles or MEs embedded in the fingertips of the elastomer when coupled to an external magnet, up to a holding force of 45N. In Guan *et al*'s study, an effective approach to optimizing the properties of hybrid MR materials is presented. The new hybrid MR materials were prepared by using the DIW3D printing technique. The optimized MR material exhibits high MR effects and has a maximum absolute and relative MR effect of 11.1 MPa and 7474% respectively. These characteristics have enabled the material to be successfully fabricated into the robot's calipers. Allowing the calipers to show a higher clamping force, 7.0 x 10^{-3}N, and a faster response rate of around 2.0s.

4. Summary and future outlook

In MREs, silicone-based materials and CIPs are the most common materials for matrices and embedded particles, separately. Additives are added to improve the performance and Mr effect of MREs. Most MRE substrates can be cured at high temperatures or indoor temperatures. In the field of MRE-based devices, traditional applications such as dampers and vibration isolators are becoming progressively more sophisticated, but shortcomings such as limited operating range, high-output requirements, and large configurations still need to be overcome. Meanwhile, the novel applications of MREs have been explored extensively, such as MRE peristaltic pumps and MRE soft robots. In these applications, researchers utilize the deformation of MRE under magnetic fields, although the magnetic-mechanical interaction is still not clear. Some amazing shapes could be realized in MRE soft robots, which shows dramatic advantages compared with rigid robots.

With developments of science and technology in MREs, many opportunities with inevitable challenges have emerged. Systematical research of MREs broadens future applications. Raw materials, morphology of magnetic particles of MRE, the model of MREs, and the control strategies of MRE should be paid high attention for the creation of high-performance MRE based devices.

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