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Research and Development of Vibration Dampers Based on Magnetorheological Elastomers

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Abstract

As one of the magnetorheological materials, magnetorheological elastomer (MRE) possesses unique solid properties that give it excellent mechanical properties. In the presence of an external magnetic field, the force, magnetic and electrical properties of the MRE also vary with the magnitude and direction of the magnetic field. This has led to a wide range of applications in the field of shock absorbers. This paper presents the properties of magnetorheological elastomers and the latest research status in the field of shock absorbers, and finally examines the potential and challenges for the development of MRE in the field of shock absorbers.

Subject Areas

Intelligent Materials

Keywords

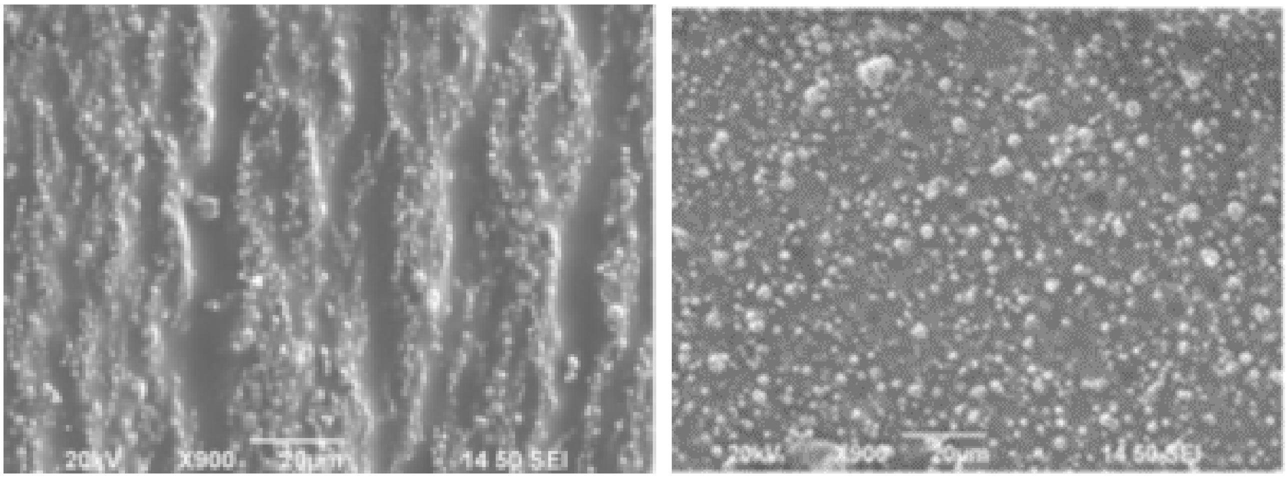
Magnetorheological Elastomers, Mechanical Properties, Vibration Dampers

1. Introduction

Mechanical vibrations are an inevitable phenomenon in social production and life. In most cases, mechanical vibration is a phenomenon that we do not want to see: it reduces the comfort of the car, the service life of some highly sophisticated instruments, etc. In order to minimize the harmful effects of mechanical vibration, the prevailing practice is to use vibration isolators to reduce the transmission of harmful vibrations. Common dampers include spring dampers and rubber dampers. As these isolators are passive vibration isolators, a rubber isolator with fixed stiffness can usually only be used in a narrow range of frequencies to provide good damping. If the external excitation frequency range changes, the vibration isolation performance of the rubber vibration isolator will be greatly reduced, or even the phenomenon of "resonance" occurs. A new smart material—magnetorheological elastomers (Magnetorheological Elastomer, MRE)—is prepared by mixing together a polymer matrix, additives and magnetic particles in a certain ratio. In contrast to other magnetorheological materials, the matrix of magnetorheological elastomers is usually a polymeric material such as rubber or resin, where the internal particles are fixed inside the matrix during the moulding process and the material is solid when moulded. Thus overcoming the problems of particle settling and poor sealing is common with other magnetorheological materials. Its stiffness and damping can vary with the external magnetic field, and it inherits the excellent performance of magnetorheological fluid such as controllable, reversible and fast response, and at the same time has the characteristics of good stability, not easy to wear and repeatability, which can be widely used in the field of high-tech vibration isolation.

2. Introduction to Magnetorheological Elastomers

Magnetorheological elastomers are magnetorheological smart materials in solid form. The solid form of magnetorheological elastomers completely avoids the problems of settling and sealing magnetorheological fluids, and therefore magnetorheological elastomers have a wider range of applications and can also be used as part of the force structure of an object, which is highly universal. Magneto-rheological elastomers generally consist of three components, namely magnetic particles, a matrix and additives, where the substrate is mostly a flexible polymer material such as rubber, and the magnetic particles must move with the magnetic induction lines of the applied magnetic field to form chains. The common magnetic particles are carbonyl iron powder and hydroxy iron powder. Magneto-rheological elastomers are divided into anisotropic and isotropic magneto-rheological elastomers, depending on whether they are exposed to a magnetic field during curing. Its internal microstructure is shown in **Figure 1**. Magnetorheological elastomers with various anisotropic properties are better and more widely used. When a magnetic field is applied, the chain of magnetic particles inside the magnetorheological elastomer changes its overall mechanical and electrical properties, modulus and damping, capacitance and resistance all change regularly. When the magnetic field disappears, the material regains its original properties and the response time to this change is in the millisecond range, with a rapid response. Thanks to this property, magnetorheological elastomers can be used in the field of vibration and noise reduction in all types of machines. Compared to magnetorheological liquid dampers, magnetorheological elastomeric dampers offer precise modulus control, light weight and simple construction, and can be used as an internal structure for machines without the need for additional springs to provide stiffness support, regardless of size. Research on magnetorheological elastomeric dampers is still in its infancy and therefore has high research value and potential for future development.



(a) (b)

Figure 1. Images of particles inside each isotropic and anisotropic magnetorheological elastomer. (a) Anisotropic magnetorheological elastomers; (b) Isotropic magnetorheological elastomers.

3. Status of Research on Magnetorheological Elastomeric Dampers

3.1. Institutional Design

The principle of magnetorheological elastomer dampers is to use the viscoelasticity of MREs [1]. The presence of damping allows the kinetic energy of a vibrating object to be dissipated into internal energy, allowing it to have both dynamic modulus and damping. At the same time, the dynamic modulus and loss factor are dependent on the magnetic flux density and we can control their performance by adjusting the magnitude of the external magnetic field. Unlike magnetorheological fluid dampers, which operate in the pre-yield region of the elastomer and cause irreversible damage to the MRE if the yield limit is exceeded, magnetorheological fluid dampers operate in the post-yield region. MRF dampers must be reciprocated by special mechanical devices in order to use the shear yield stress of the magnetorheological fluid as a damping force and are therefore only suitable for use in single-degree-of-freedom movements. The MRE damper, on the other hand, can operate normally in a multi-degree-of-freedom environment. The MRF damper only operates in shear mode, while the MRE damper can operate in shear, squeeze and mixed modes [2], making it more adaptable and easier to design and manufacture. Unlike conventional passive viscoelastic dampers which have fixed stiffness damping and can only operate within a certain frequency range, if the excitation frequency is outside a certain range, the damper will fail. The MRE damper allows the stiffness and damping to be adjusted by an applied magnetic field, resulting in excellent damping over a wider frequency range [3]. Ginder [4] of Ford Motor Company invented the world's first magnetorheological elastomer damper and tested its dynamic mechanical properties, showing that the damper stiffness increased approximately linearly with the applied magnetic field and was 40% greater at saturation than at zero field. MRE-based dampers are expected to improve the NVH disadvantage properties of a given vehicle without affecting vehicle dynamics or other NVH, and the technology can be applied to a wide range of vibration isolation and motion control problems on vehicles and during the manufacturing process. As shown in **Figure 2**, Leng D [5] *et al.* designed and fabricated a coupled shear-squeeze hybrid mode MRE damper and tested it. The results showed that the frequency shift characteristics of the damper were linearly related to the volume fraction of the magnetic particles and the applied magnetic field, and the damping capability was significantly enhanced by the controlled current, providing a new idea for the use of MRE dampers. (**Figure 3**)

Shuaishuai Sun [6] *et al.* used multilayer magnetorheological elastomers to design an adaptive tuned damper that could absorb two types of vibration in the torsional and translational directions. It was found through experiments that the MRE damper achieved double the intrinsic frequency and had a great role in absorbing vibration energy at these two intrinsic frequencies. As shown in **Figure 4**, Berhrooz M [7] *et al.* have designed a variable stiffness MRE damper. The damper has a 12mm block shape MRE with symmetrical top and bottom blocks and four sets of coils distributed at the ends of the two MREs. A shear test rig was built and the Bouc-Wen model was used to represent the output force versus displacement. Finally, the MRE damping system was experimentally confirmed to have good frequency shifting characteristics. (**Figure 5**)

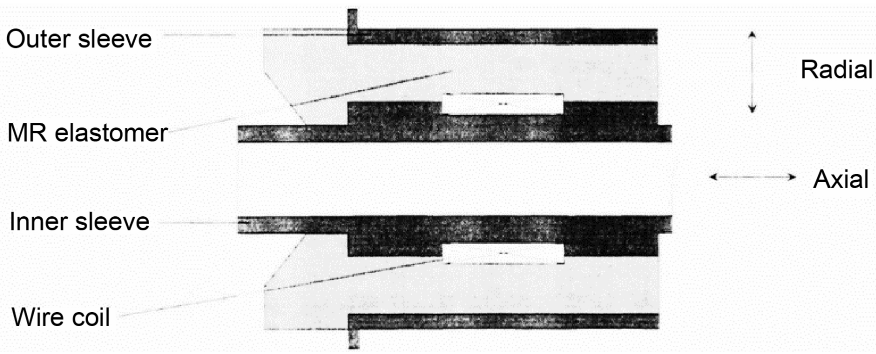


Figure 2. MRE damper invented by Ginder *et al.*

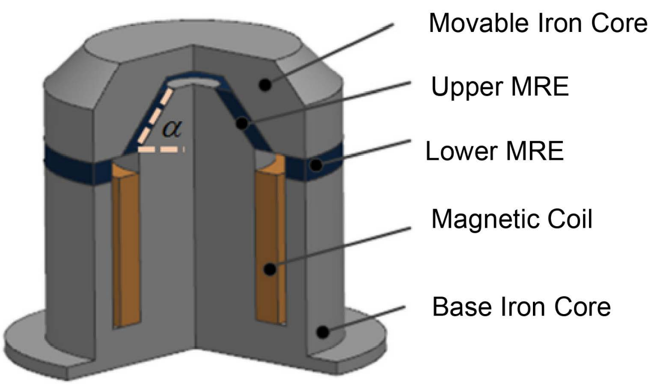


Figure 3. Coupled shear-extrusion hybrid MRE damper.

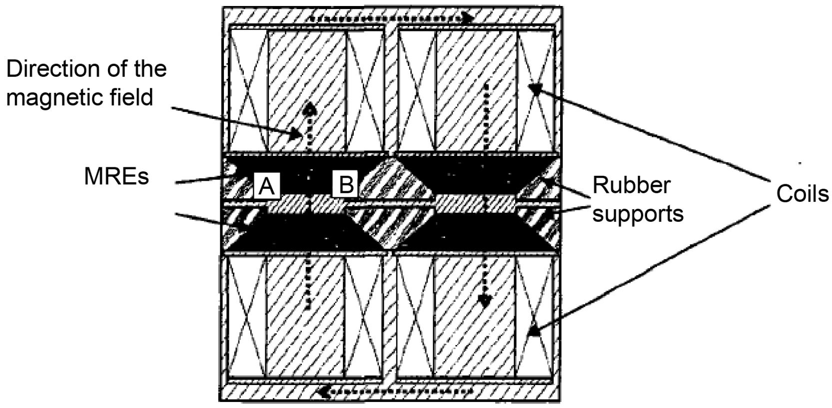
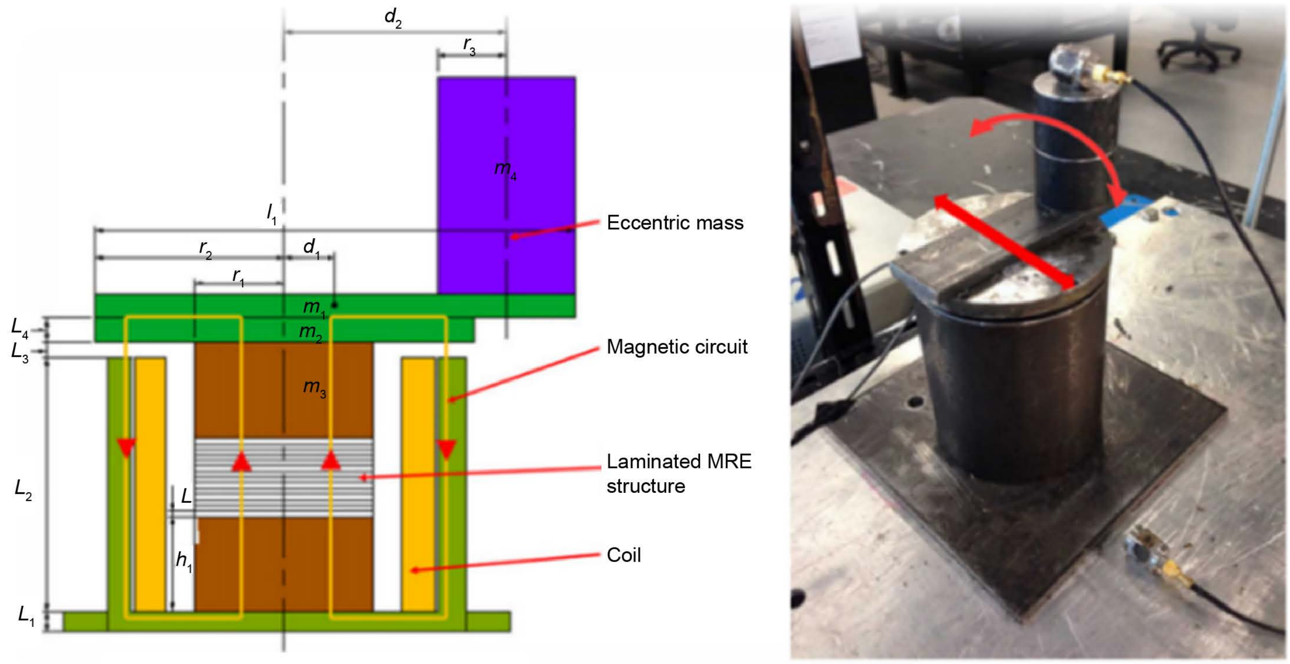


Figure 4. Multi-layer adaptive tuning damper.



(a) (b)

Figure 5. Dual module MRE damper. (a) Schematic sketch; (b) Prototype.

Bazinenkov [8] designed a simple structured MRE damper with an overall structure consisting of 1) base, 2) permeable core, 3) coil, 4) permeable magnet, 5) MRE, and 6) gap. The MRE can move up and down in the gap under load excitation, providing vibration isolation. The magnitude of the magnetic field is controlled by adjusting the amount of current in the coil, which ultimately changes the stiffness and damping of the MRE. As shown in Figure 6, Guojiang Liao [9] *et al.* An MRE-based variable stiffness damping damper, this damper works similarly to the above article, with the specific structure of 1) base, 2) coil, 3) conductor, 4) shear platform, 5) core, 6) MRE, 7) voice coil motor, and 8) base. The initial force to the damper is provided by three voice coil motors and the output force is experimentally verified to be proportional to the shear rate. (Figure 7)

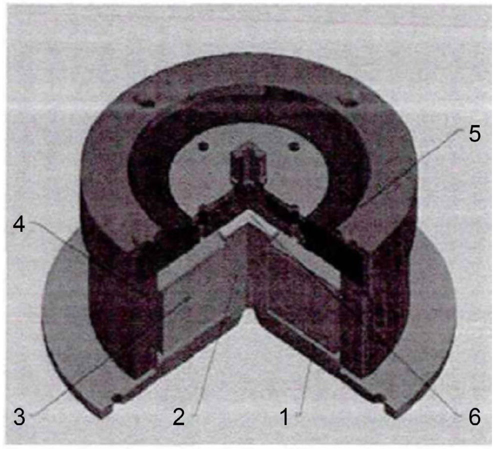


Figure 6. Simple MRE damper structure.

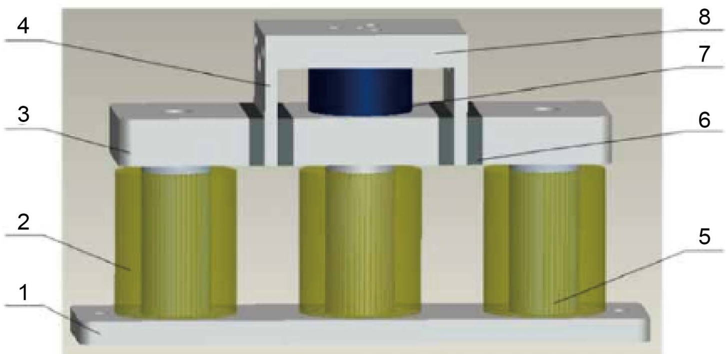


Figure 7. MRE-based variable stiffness damper.

Shuaishuai Sun [10] *et al.* also designed an MRE damper for buildings, which was tested using simulated seismic waves and scanned sinusoidal signals, and the results showed that the damper outperformed all other passively tuned mass dampers. The structure always contains four square magnetorheological elastomer structures, eliminating the magnetic circuit gap problems of past designs, and the magnetic field required by all four elastomers is a closed circuit, facilitating the acquisition of larger magnetic fields. As shown in **Figure 8**, Mikhailov [11] *et al.* have designed an active vibration isolation platform based on MRE. Active dampers based on MR elastomers can be used as micro- or nano-positioning actuators for vibration-insulated objects, with the advantages of isolating a wide range of displacements, more efficient absorption of vibration energy, active control of amplitude-frequency characteristics, and positioning with millisecond response times and nano-operational accuracy. (**Figure 9**)

Wen Yongpeng [12] *et al.* designed an MRE damper for railroad vehicle damping. A flexible vehicle body model with magnetorheological elastomeric power absorber is established, and the optimal design frequency expressions for rigid and elastic vibration of the vehicle body are fitted by multiple regression analysis, and the problem of determining the parameters of magnetorheological elastomeric power absorber is studied in detail. The feasibility and performance

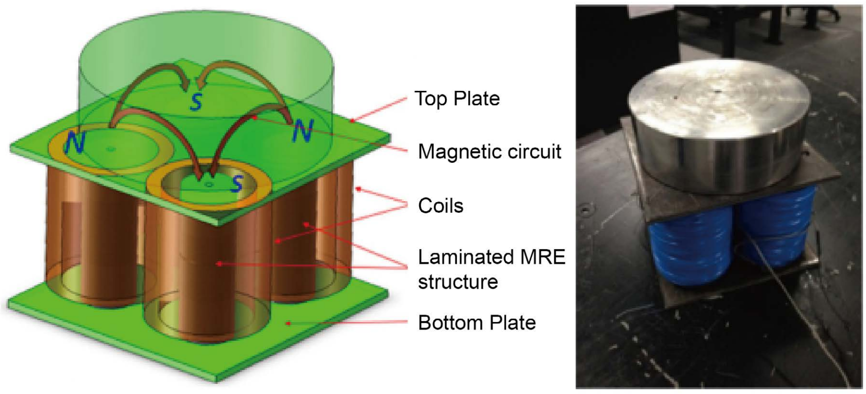


Figure 8. Damper for MRE's in buildings.

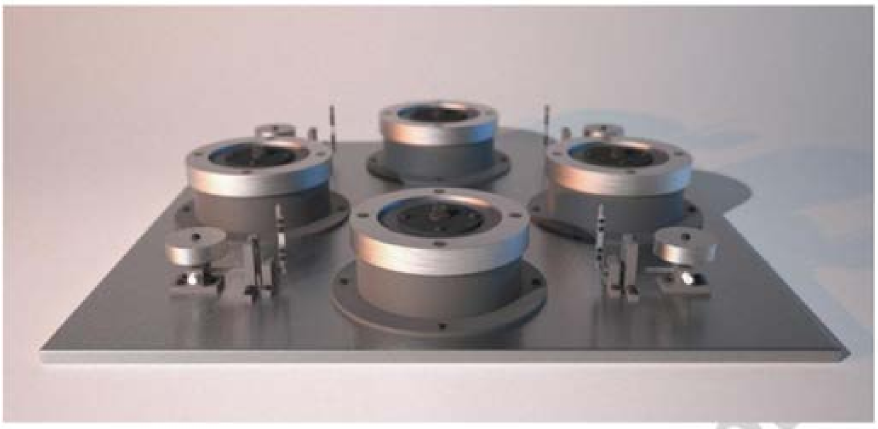


Figure 9. MRE-based active dampers.

of magnetorheological elastomeric power absorbers in practical applications were evaluated using the Sperling multiplication index. The results show that replacing a dynamic absorber without magnetorheological elastomer with a magnetorheological elastomer dynamic absorber can effectively reduce the vibration of the vehicle body. This is shown in Figure 10. Weihua Li *et al.* [13] presented the design and development of a magnetorheological elastomer isolator for a seat suspension system. By changing the stiffness of the magnetorheological elastomer isolator through a controlled magnetic field and selecting a suitable control strategy, the intrinsic frequency of the system can be changed to avoid resonance, thereby reducing the vibration energy input to the seat from the vehicle and thus suppressing the seat response. The experimental results show that the developed magnetorheological elastomer vibration isolator has a better vibration damping effect compared with the passive vibration isolation system, indicating its great potential for application in automotive seat vibration control. (Figure 11)

3.2. Control Strategy

Researchers at home and abroad have proposed many control methods for magnetorheological elastomers, among which more applications are PID control,

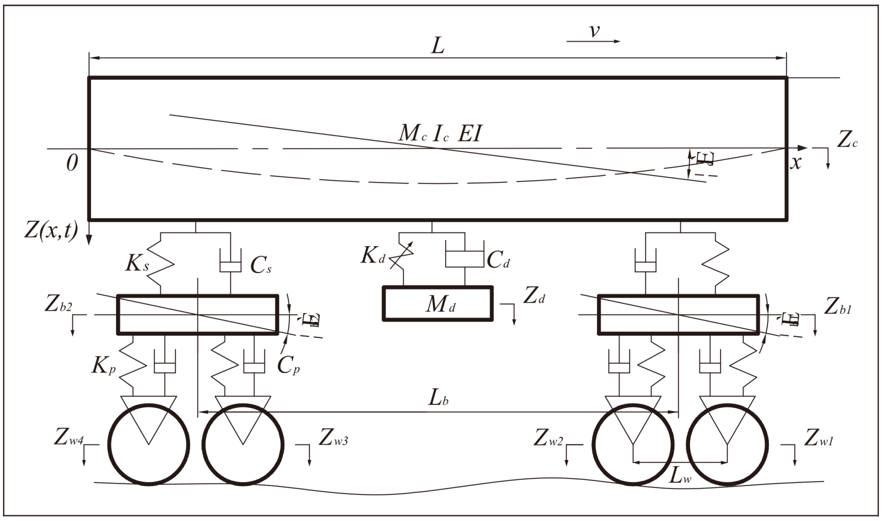


Figure 10. MRE-based flexible car body model.

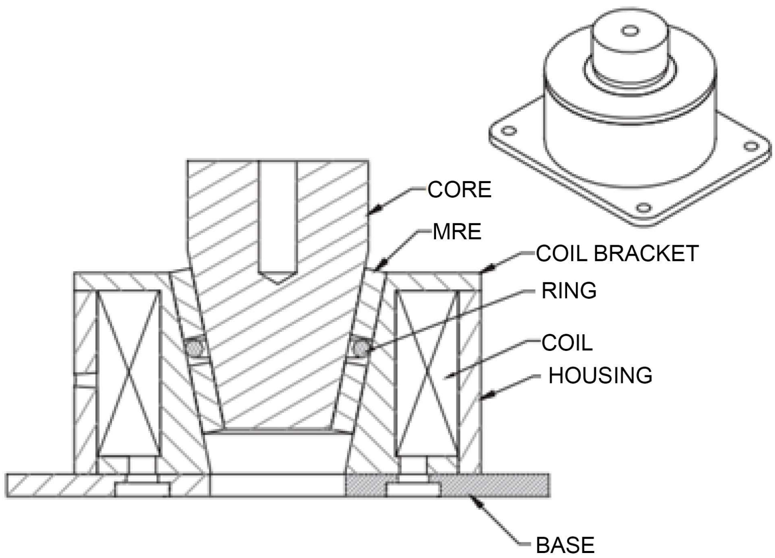


Figure 11. Car Seat MRE Damper.

fuzzy control, adaptive control, ON-OFF control, neural network control, canopy control, etc. The most common ones are PID control and fuzzy control. The core of semi-active control is to adjust the output signal in real time according to the input signal, specifically to regulate the size of the damper output current according to the characteristics of the vibration excitation, this process is millisecond, and we want to find a control strategy that has the optimal vibration isolation performance and minimum energy consumption.

PID control is one of the most classic control strategies and has a long history. It has the advantages of simple structure, easy implementation, and robustness. Yu Fujie [14] *et al.* designed a PID controller for the MRE vibration isolation system and verified the effectiveness of the control strategy by numerical simulation, resulting in a maximum impact load reduction of 11.6% compared to the passive control. Kim [15] *et al.* designed a tunable damper with real-time adaptive tuning of time-varying perturbations and performed dynamic mechanics experiments using a PID controller, which showed that the device could be automatically tuned to 56 Hz to 67 Hz at a magnetic field of 100 mT to minimize the vibration of the primary system.

Fuzzy control has the advantage of not relying on a specific mathematical model and has been widely used in the design of controllers for vibration isolation systems. Guojiang Liao [16] *et al.* proposed a phase-based magnetorheological elastomer damper fuzzy logic controller for fast tracking of the excitation frequency. Based on the characteristics of fuzzy control, the controller does not depend on the exact relationship between the magnetorheological elastomer damper current and the resonant frequency. Simulation and experimental results show that the magnetorheological elastomer damper can be tuned correctly within a few seconds when the excitation frequency changes. (**Figure 12**)

In addition to the above classical control strategies, Guo Yingqing [17] *et al.* proposed an optimal fuzzy fractional order PID (OFFO-PID) algorithm for vibration isolation and damping of precision platforms of MRE equipment. The results show that the OFFO-PID algorithm can effectively reduce the dynamic response of the precision platform system. Compared with fuzzy fractional order PID algorithm and conventional PID algorithm, OFFO-PID algorithm has better performance.

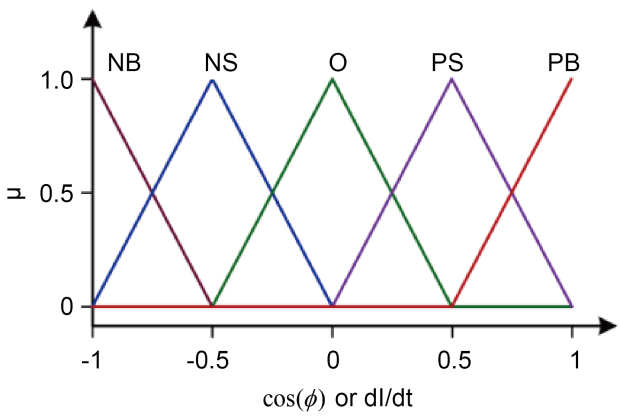


Figure 12. Affiliation function of fuzzy controller.

4. Summary and Outlook

Through the comparison of magneto-rheological elastomers with magneto-rheological fluids, it solves the problems of particle deposition and sealing of magneto-rheological fluid. In a complex mechanical system, the operation produces multiple degrees of freedom, complex vibrations, and different working conditions with varying vibration characteristics. Traditional passive vibration dampers are unable to meet the full range of vibration damping needs. The structure of the magnetorheological elastomer damper is similar to that of the traditional rubber damper, and its stiffness and damping can be altered by changing the current. This enables it to meet the complex damping needs of multi-variable working conditions. Although research on magnetorheological elastomers is still in the laboratory stage, its great potential in the field of vibration and noise reduction of mechanical systems is evident to all, and it is expected to achieve large-scale applications in automotive, machinery, aerospace, military, construction, medical and other fields in the future.

There are still many limitations and problems that need to be solved for magnetorheological elastomer dampers to be successful in practical applications. The most important disadvantage of MRE is the slow response time of the magnetic field (or current). This leads to limitations in the need for fast acting shock absorbers. The second problem is the magnetic field loss, which sometimes requires a very large coil current to create the field strength conditions for the magnetorheological elastomer to work. It can lead to inefficient energy use. More research is needed to investigate the normal operation of magnetorheological elasticity under low current conditions. There are no commercially available MRE materials at this stage. This is because the material requirements for MREs are different for each application device. Therefore, after making a decision on the application project, MREs are made to meet the application requirements such as the amount of damping force and response time. Most of the current studies related to magnetorheological elastomers are universal and mechanistic in nature, with few studies specific to mechanical systems. Magnetorheological elastomeric dampers have a promising future in the field of vibration and noise reduction in mechanical systems, and further research is needed by researchers.

Conflicts of Interest

The authors declare no conflicts of interest.

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