Dynamics, Measurement and Control Division Newsletter
DYNAMICS
Dmc JSME

*This is a translation of featured article in the DMC division newsletter No. 60. The original article in Japanese are published on 24th July 2017

Applications of Stiffness-controllable Magnetorheological Elastomers

Toshihiko Komatsuzaki

College of Science and Engineering, Kanazawa University, Japan

1. Introduction

The development of damping technology is important not only from the standpoint of preventing the destruction of or damage to mechanical structures but also from the perspective of ensuring safety and comfort. Generally, passive damping measures, such as low stiffness isolators and vibration absorbers are employed. However, in these cases, damping features are uniquely determined by the used materials. In addition, when inexpensive configuration and high reliability are concerned, the damping function might become insufficient in situations that exceed those considered in the original design. On the contrary, active control is a method that is different from the passive approach. Using this method, the excitation is forcibly controlled through the power generated by an actuator. Although the damping features are ensured to be considerably improved, practical concerns, including device complexity and cost, occur. A semi-active approach by making parameters variable, which was not possible with the passive approach, including the attenuation coefficient, is a compromise between the aforementioned methods. It is possible to maintain the reliability inherited from the passive approach while achieving a level of control close to that of the active approach at a comparatively low cost.

Materials whose characteristics can be changed according to external physical stimuli are known as functional materials. Through a combination with semi-passive control rules, studies aiming to realize functional structures that are more intelligent have been reported. Herein, magnetorheological elastomers (MREs) have been developed and applied to damping, vibration isolation, and soundproofing technologies. Magnetorheological fluids (MRFs) are well-known functional fluids, the apparent viscosity of which changes in response to external magnetic fields. Because of its high change range and sensitive responsiveness, a broad range of applications, e.g., attenuation-adjustable dampers, has been explored. However, in addition to the essential problem as a fluid, the sealing characteristics of MRFs are required to be ensured. Various issues that are required to be addressed, such as the sedimentation and cohesion of distributed particles as well as time-related deterioration, have also been raised. On the contrary, the development and practical research on MREs and the apparent viscosity, which changes according to external magnetic fields, have continued to grow in recent years. In addition to the fact that MREs can resolve the abovementioned issues associated with MRFs by fixing the dispersion of the magnetic particles within the elastomer, its feature of stiffness variability, which has not received considerable attention until now, gives MREs the potential to be used as functional materials in a wide range of fields. Functional development aimed at improving these characteristics, particularly research on MRE applications for damping, vibration isolation, and soundproofing from the perspective of vibration engineering, is being continuously investigated.

This paper provides an overview on rigidity variability, which is a remarkable change in the physical properties of MREs. Subsequently, as part of the approach involving the use of MREs from an engineering perspective, some cases wherein the authors have participated were introduced. These include the application of MREs to variable-characteristic vibration isolation mounts for supporting devices and structures, to the spring elements of dynamic absorbers, which are known as typical damping devices, and the development of variable-rigidity dynamic absorbers, which can achieve damping effects across a broad range of frequency domains while maintaining a simple structure for natural frequency variability caused by rigidity changes due to external magnetic fields.

2. Overview and Features of MREs

MRE, as an example of magnetic responsive materials, is a composite with a non-magnetic substrate and fixed distribution of magnetic particles. The apparent elasticity rate and attenuation characteristics reversibly change according to the external magnetic field. This is referred to as rigidity variability. As a functional material with this characteristic, which has not received considerable attention to date, MREs promise potential applications in a wide variety of damping devices.

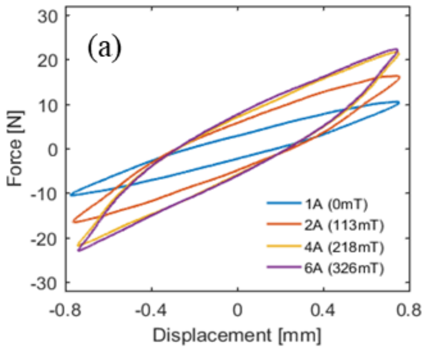
When MREs were proposed for the first time, their application in medical measuring devices was investigated by Rigbi and Jilken1) in 1985. However, it was clearly defined in the study by Jolly et al.2) until 1996. Since then, a wide variety of studies have been conducted on MREs. In the early stages of their development, attention was paid on resolving the issues of particle sedimentation found in MRF. Since MRE has an advantage in fixing particles within an elastomer, there is no need to deal with particle sedimentation and liquid leakage. In addition, it is easy to increase the functionality of mechanical structures by forming MREs with shapes desired for specific elastomers and replacing the existing rubber materials.

In contrast to MRFs whose apparent viscosity changes, MREs mainly involve changes in elastic properties since the elastomer materials in which elastic properties are dominant for substrate materials are used. In other words, MRFs support the usage of the characteristics post-yielding, whereas MREs support the usage of the characteristics pre-yielding. Additionally, when integrating attenuation elements within MRFs, their resistance property can only become effective in one direction. Using MREs, this distortion is not limited to one direction. If this point is effectively used, it can be a clearly distinguishing point for MRFs.

MREs are normally created as a combination of magnetic particles, elastomer, and additive agents. The physical properties of MREs depend on the binding strength of magnetic particles. The changes in the physical properties increase with the strength of the magnetic field. Magnetic particles with high permeability and low residual magnetization are generally used as magnetic-field responsive elements, while natural rubber or silicon rubber is commonly used for the substrate. The magnetic binding force, which controls the variation in physical properties, becomes proportionately large as the distance between the particles decreases. However, since magnetic particles are fixed within the substrate in MREs, these particles can be brought close by employing a magnetic field during the hardening process after stirring and degassing. If magnetic particles can be fixed by forming a long chain of magnetic particles in a specific direction, MR effects greater those obtained via even distribution may be realized.

MREs generally employ a semi-active control method. In concrete terms, their application is being investigated in relation to vibration and sound control, e.g., for dynamic absorbers, vibration isolation mounts, and structural elements. Furthermore, there are studies on foundational physical properties, which aim to increase the feature change range, in addition to investigations on the theoretical forecasting of viscoelastic changes in relation to magnetic fields. However, these are not yet complete in terms of material development, logic, and application. Additional research is expected to further enhance the property of the material and to exploit the full use of the stiffness variability.

As an example, the features of an MRE employing two-part silicon rubber for the substrate and iron filings with a particle diameter of approximately 10 μm at a volumetric ratio of approximately 40% were investigated. Such MREs can be hardened at room temperature. The samples were inserted into the closed magnetic circuit comprising a coil and iron core, while the deformation and restoring forces were simultaneously measured by dynamically applying force in the shear direction and changing the excitation amplitude and frequency$^{3)}$. First, as shown in Figure 1, the excitation amplitude is fixed and the relationship between deformation and restoring forces with different excitation frequencies is compared. The incline of the loop (elasticity), area within the loop (attenuation), and loop shape changed with increasing magnetic field. Subsequently, Figure 2 shows the results solely focusing on the elasticity of MREs and evaluating their dependency on the excitation frequency and excitation amplitude. The changes in elasticity are dependent not only on frequency but also on amplitude. The influence of the latter is particularly significant. In addition to essentially being a viscoelastic body, MRE features dependent on frequency and amplitude outside magnetic fields should be considered for modeling and application to the device design.



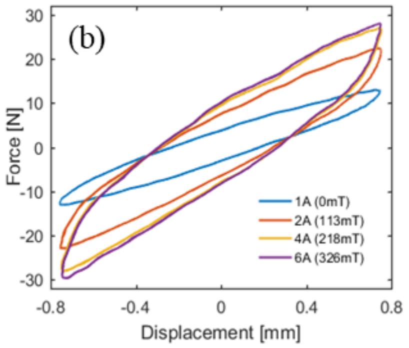


Fig. 1 Force–displacement curves under different levels of electric current with excitation amplitude x_0 = 0.75 mm: (a) f = 1 Hz and (b) f = 15 Hz.

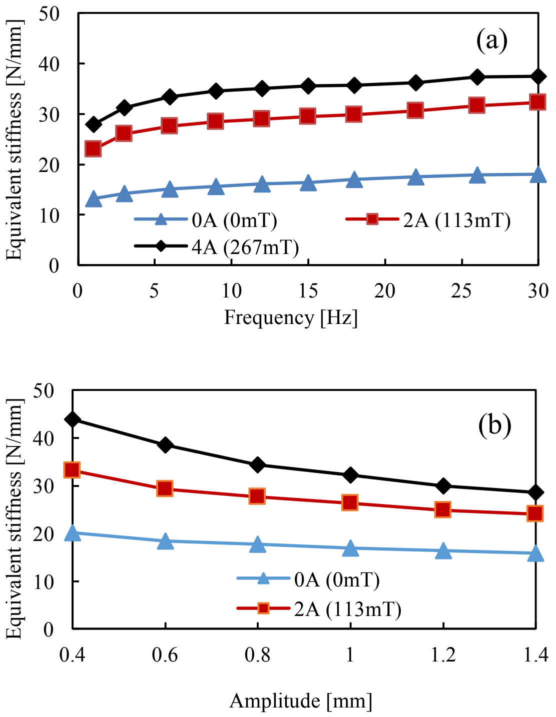


Fig. 2 Stiffness change characteristic for different applied currents: (a) the values are plotted against excitation frequency under constant excitation amplitude x_0 = 0.75 mm and (b) the values are plotted against the excitation amplitude under constant excitation frequency f =15 Hz.

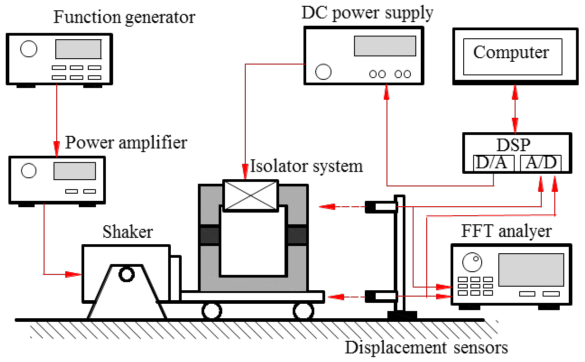


Fig. 3 Experimental setup for magnetorheological elastomer (MRE)-based vibration isolator.

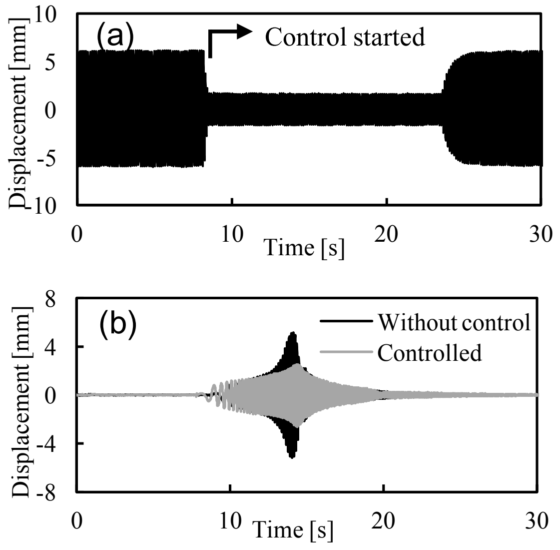


Fig. 4 Displacement response of a base-excited 1-DOF system under (a) sinusoidal excitation and (b) swept-sine excitation.

3. Semi-Active Control Through Vibration Isolation Mounts Applying MRE

Examples of MREs being applied to feature-variable vibration-isolated mounts supporting mechanical materials are introduced. A semi-active vibration control using on–off variable-rigidity control rules is created, which switches between two minimum and maximum values of rigidity, in relation to scaled structures$^{3),4)}$. Figure 3 shows an experimental device with a vibration system for receiving displacement vibration in the horizontal direction of the foundational unit. The top of the magnetic circuit, made of coils and iron core, is observed as the mass in the vibration system, while MREs are observed as springs and attenuation elements. Controlled vibration was passed from the foundation section to the upper section. The spring constant element corresponds to being off when there is no magnetic field and on when applying 5 A. In addition, the coil-applied current following the control rules is determined based on the load mass and displacement measured in the foundational unit of the vibration system.

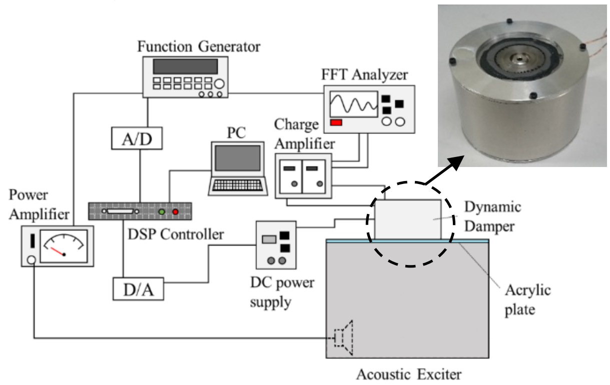


Fig. 5 Schematic of the broadband variable-stiffness DVA.

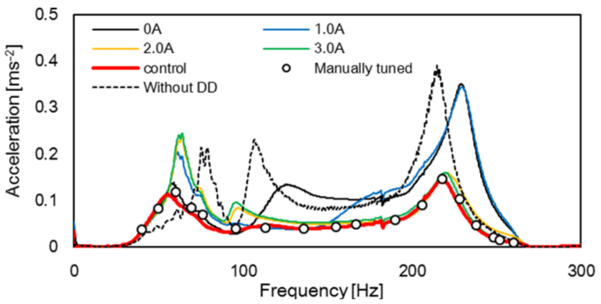


Fig. 6 Frequency response obtained via automatic tuning of the damper's natural frequency.

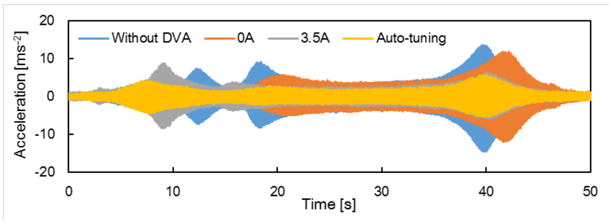


Fig. 7 Time histories obtained when the DVA property was fixed corresponding to the applied currents of 0 and 3.5 A and when the DVA was automatically tuned in real time.

As a control example, Figure 4 shows time waveforms for a case wherein sinusoidal excitation is applied to the base near the resonance point and a case wherein sweep-sine excitation passes the resonance point. When performing controls according to rigidity switchover rules, the displacement is reduced to half or less of that without control. The increase in the switchover rigidity difference increases the violation isolation that can be achieved. It is therefore important to develop both materials that can lead to significant rigidity variation and design a framework for effectively marking the magnetic fields with a small amount of current. By combining the variable-rigidity control rules with MRE, efficient vibration control is possible.

4. Application to Variable-Rigidity Dynamic Absorbers

Dynamic absorbers are devices whose natural frequency is adjusted in accordance with the vibration frequency to be controlled. By being attached to a target object, the control effects of absorbers are obtained near the target frequency. However, since dynamic absorbers are basically passive devices, their mass and rigidity are constant, leading to an issue that their control effects are smaller in vibration frequency ranges than those of the designed ones. To resolve this issue, rigidity variability is employed because of the external magnetic field by applying MREs to spring elements in dynamic absorbers. A variable-rigidity dynamic absorber that can regulate itself to the state at which its damping effects are the highest in line with the disturbance frequency[5)-7)] is introduced.

Figure 5 schematically shows the experimental device to evaluate the damping characteristics of the variable-rigidity dynamic absorber. This absorber uses part of the iron core as the mobile mass and comprises coils, a ring-shaped MRE, and a housing section. This structure has an integrated magnetic circuit for removing the external power. Additionally, it has a magnetic closed loop formed along the inside core and the magnetic field is marked efficiently in the MRE. In contrast to 60 Hz in the non-magnetic field, the natural frequency increased up to 250 Hz when applying a current of 3.5 A.

Figures 6 and 7 show the frequency response and time histories, respectively, when acoustically exciting a board using a 50–300-MHz frequency sweep-sine wave. The natural frequency of the dynamic absorber is controlled to synchronize with the excitation frequency in real time. From these results, it can be observed that when the natural frequency of the dynamic absorber is synchronized in real time compared to the case wherein the features are fixed, it is able to control frequency across a wider range of bandwidths. The attenuation rate of this dynamic absorber is high at approximately 0.2, which ensures further improvement in the damping performance.

5. Conclusions

This paper provided an overview of MRE, which enables apparent rigidity to vary in response to magnetic fields. Additionally, as an application of MRE in seismic engineering, this study introduced cases of vibration isolation using semi-active vibration isolation mounts applying variable-rigidity control rules in addition to the case of the damping of structures using a disturbance frequency-tuned variable-rigidity dynamic absorber. Over approximately past 20 years, a considerable research related to MREs has been reported, the understanding of which is progressing. However, there are many issues that need to be resolved in terms of practical needs and there is still ample room for investigation. In concrete terms, it is essential to develop a material from which a major amount of variation can be achieved with low power consumption. In addition to the materials themselves, it is necessary to investigate the design of efficient magnetic control application methods and control algorithms that maximize the utilization of rigidity variability. On the contrary, in addition to the characteristics discussed up to this point, it is a major advantage that the development of these materials is inexpensive. In the future, in addition to foundational research on improving the physical properties of materials, elastomers are planned to be applied to a wide variety of fields other than damping technology.

A previous study[8)] has covered typical research on MREs and introduced cases wherein they were applied to the investigations of MRE stacking, sensors, valves, and actuators, in addition to dynamic absorbers and vibration prevention mounts and cases of research into the modeling of the physical properties of MREs. There are also comments on the current issues and the future outlook for MRE development.

Reference Documents

1) Rigbi, Z. and Jilken, L., The response of an elastomer filled with soft ferrite to mechanical and magnetic influences, Journal of Magnetism and Magnetic Materials, **37** (19832) pp. 67-76.

2) Jolly, M. R., et al., The magnetoviscoelastic response of elastomer composites consisting of ferrous particles embedded in a polymer matrix, Journal of Intelligent Material Systems and Structures, **7** (1996), pp. 613-622.

3) Nguyen, X. B., Komatsuzaki, T., Iwata, Y., and Asanuma, H., Fuzzy semiactive vibration control of structures using magnetorheological elastomer, Shock and Vibration, **2017** (2017), 3651057.

4) Komatsuzaki, T., et al., Development of magnetorheological elastomers and application to semi-active vibration controls, Transactions of the Japan Society of Mechanical Engineers C, **77-784** (2011), pp. 4510-4520.

5) Komatsuzaki, T., Iwata, Y., and Inoue, T., Experimental investigation of an adaptively tuned dynamic absorber with self-sensing property, Experimental Mechanics, **56-5** (2016) pp. 871–880.

6) Komatsuzaki, T. and Iwata, Y., Design of a real-time adaptively tuned dynamic vibration absorber with a variable stiffness property using magnetorheological elastomer, Shock and Vibration, **2015** (2015), 676508.

7) Komatsuzaki, T., Inoue, T., and Terashima, O., Broadband vibration control of a structure by using a magnetorheological elastomer-based tuned dynamic absorber, Mechatronics, **40** (2016), pp. 128–136.

8) Li, Y., Li, J., Li, W., and Du, H., A state-of-the-art review on magnetorheological elastomer devices, Smart Materials and Structures, **23-12** (2014), 123001.