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PREPARATION AND APPLICATION OF HIGH-PERFORMANCE MAGNETO/ELECTRORHEOLOGICAL COMPOSITES

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Abstract. It is a crucial issue to reduce the vibration of civil structures, mechanical structures and space structures. Passive energy dissipation devices based on elastomers, metal dampers and viscous dampers only can control the vibration of structures in a narrow frequency. Smart materials with tunable stiffness or tunable damping could actively control the vibration of structures within a wider frequency. Magneto/electro-rheological composites including magnetorheological fluids, electrorheological fluids, magnetorheological elastomers and electrorheological elastomers are such a kind of smart materials. These materials are prepared by dispersing electric polarized or magnetic polarized particles within carrier liquids or polymer matrix. Under an applying electric or magnetic field, their viscosity, yield stress or dynamic viscoelasticity change fast and reversibly. During the past decades, we investigated the mechanisms of magneto/electro-rheological materials. By controlling the morphology of the active particles, we developed some high-performance magneto/elector-rheological composites, such as Fe-Co nanoparticles based magnetorheological fluids, graphene oxide-wrapped core-she structured amorphous titania nanoparticles based electrorheological fluids, flower-like particles based magnetorheological elastomers. TiO_2/urea core-shell particles based electrorheological elastomers and so on. We used them to fabricate smart devices that could reduce the vibration of various structures in wide frequency, such as variable stiffness tuned mass damper based on conical magnetorheological elastomer isolators, stiffness tunable viscoelastic damper based on electrorheological elastomers, wind-induced vibration control of a constructing bridge tower with MRE variable stiffness tuned mass damper and so on. To further wider their applications in some other fields, we used those materials as smart tissue engineering scaffolds, brain-computer interface electrodes, and stiffness tunable artificial muscles. Some typical works will be introduced in this presentation.

Key words: magnetorheological fluids; electrorheological fluids; magnetorheological

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elastomers; electrorheological elastomers

1 INTRODUCTION

Because of its excellent modulus tunability, magnetorheological elastomers (MRE) have great potential for vibration control for civil structures, mechanical structures and space structures. As early as 1997, Ford [1] developed a variable stiffness automotive suspension liner using magnetorheological elastomers to improve ride comfort. Blom [2] used MRE isolators for flat panel sound insulation, which significantly reduced the energy flow input into the flat panel compared to ordinary rubber. Opie [3, 4] has developed a semi-active vibration isolator based on MRE material, which can reduce the resonance response by 16% - 30% by adjusting the stiffness forward.

In recent years, the enormous potential of MRE in the field of base isolation in civil engineering has attracted the attention of researchers. Firstly, researchers focused on the effectiveness of MRE application in civil engineering seismic isolation through simulation and scaled experiments [5, 6, 7]. Meanwhile, some studies worked on the magnetic excitation efficiency in order to achieve lightweight design of the MRE isolators. Behrooz [8] designed a variable stiffness support with coils and MRE separately installed for the horizontal isolation of a 1:16 scale three-story frame; Li [9] designed an isolator with a coil wrapped around MRE, and the experimental results showed that the magnetic stiffness can be increased by 1530%; Wang [10] optimized the shape of the isolator to improve the magnetic field insufficient utilization of separated coils. However, the current application of MRE in civil engineering mainly focuses on horizontal variable stiffness isolation, and there is relatively little research in vertical isolation, especially establishing a real-time semi-active control isolation system to verify the actual vibration reduction effect of the support.

Therefore, this article firstly designed a semi-active vertical isolation system for equipment installed in buildings, then derived the mechanical model of MRE vertical isolators. After that, the vertical isolation performance tests were carried out to validate the effectiveness of the semi-active isolation system.

2 THE DESIGN OF MRE VERTICAL ISOLATOR

2.1 The structure of MRE isolators

As shown in figure 1, the isolator consists of two components: a load-bearing component and a magnetic excitation component. The load-bearing component has MRE-organic glass laminates, two organic glass connecting rods, and two bearing sleeves. To avoid eddy current heating, non-metallic material organic glass is used for connecting rods and the hard plates in the laminates. The hard circular plates in the MRE-organic glass laminates can bear rubber pressure and constrain lateral deformations, while the connecting rods transmit forces. The bearing sleeves are set on the upper and lower sides of the magnetic yokes, which can limit the swinging and translation of the connecting rods. On the other hand, the magnetic excitation component of the vertical isolator is composed of a coil and magnetic yokes. To ensure the intensity and uniformity of the magnetic field, the MRE-organic glass laminates are placed in the central cavity of the coil.

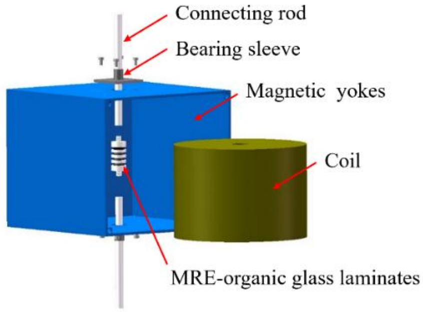


Figure 1: Exploded view of MRE vertical isolator

2.2 The mechanical model of MRE vertical isolator

With isolator dimensions and the constitutive equation of MRE proposed by Li [11], the following mechanical model of MRE vertical isolator can be derived by considering equilibrium equation and deformation compatibility equation:

$$F = \pi r^2 \left[\frac{a\varepsilon_0^{k_1} + b\varepsilon_0 + c}{2} + \left(d\varepsilon_0 + e - f\varepsilon_0^{k_2}\right)\left(\frac{|x|}{nt\varepsilon_0}\right)^{k_5} \frac{x}{nt} + f\varepsilon_0^{k_2}\frac{x}{nt} + 3\left(g\varepsilon_0^{k_3} - h\varepsilon_0^{k_4}\right)\left(\frac{|x|}{nt\varepsilon_0}\right)^{k_5} \frac{\dot{x}}{nt} + h\varepsilon_0^{k_4}\frac{\dot{x}}{nt} \right] \tag{1}$$

where F is the vertical force (Unit: N), x is the compression deformation (Unit: mm), and ε_0 is the strain amplitude. n, t and r respectively represent the number, the thickness and the radius of MRE layers. Besides, the symbols, $a \sim h$ and $k_1 \sim k_6$, are fitting parameters depend on magnetic field intensity, and given by interpolation based on table 1 and table 2.

Table 1: Values of fitting parameters $a \sim h$

H (kA/m)	a	b	c	d	e	f	g	h
0	12.83	-44.90	1.485	114.9	276.9	164.5	15.19	14.68
46	14.79	-37.40	1.394	278.9	278.9	158.4	17.60	13.99
92	19.27	-20.67	1.041	99.2	275.6	152.9	25.21	16.05
139	27.25	-18.47	0.936	-99.4	99.2	135.8	30.99	15.94
186	29.40	-27.53	1.047	-408.7	334.8	114.2	37.34	15.66

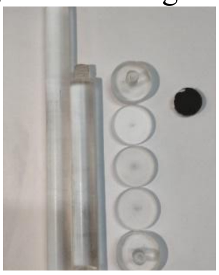
Table 2: Values of fitting parameters $k_1 \sim k_6$

H (kA/m)	k_1	k_2	k_3	k_4	k_5	k_6
0	2.325	-0.1480	-0.2880	-0.2795	4	8
46	2.441	-0.1631	-0.2757	-0.3153	4	8
92	3.205	-0.1893	-0.2629	-0.3373	4	8
139	5.083	-0.2615	-0.3286	-0.4672	3	6
186	7.492	-0.3666	-0.3679	-0.5765	2	5

3 THE VERTICAL ISOLATION PERFORMANCE TEST

3.1 The dimensions design of the tested isolator

The vertical isolator designed in the performance test is mainly used for equipment protection in buildings. As the upper equipment is close to a rigid body, it can be simplified as a mass block with a mass of 1kg. The steady-state operating frequency of the equipment is 50Hz, the load amplitude is $p_0=0.125mg$, the upper limit of target transmission ratio is 3, and the maximum compression strain is 15%. Based on the proposed mechanical model and iterative design, the following dimensions of the isolator can be obtained: r=10mm, t=5mm, and n=4. Therefore, the load-bearing component of MRE vertical isolator can be made, as shown in figure 2a and figure 2b.



a) Connecting rod, hard circular plate and MRE layer

b) Load-bearing component

Figure 2: Exploded view of MRE vertical isolator

Meanwhile, the magnetic excitation component of the vertical isolator can be designed and optimized by FEA electromagnetic model. As a result, the obtained wire parameters and coil parameters are shown in table 3 and table 4.

Table 3: Wire parameters

Diameter of copper core (mm)	Diameter of enamel-covered wire (mm)	Dc resistance at 20℃ (Ω/km)	Weight per unit length (kg/km)
2.44	2.54	3.75	42.2

Table 4: Coil parameters

Height (mm)	Inner diameter (mm)	Thickness (mm)	Rated current (A)	Maximum magnetic intensity(kA/m)
140	36	82	14	123

3.2 The experimental set-ups of the vertical isolation test

The test was conducted in the State Key Laboratory of Industrial Equipment Structure Analysis of Dalian University of Technology. The sweeping frequency load was applied by the ES-10D-240 electric shake table. Installed on the shake table with a bolt, a single degree of freedom (SDOF) dynamic system is formed by a 1kg mass block, two connecting rods, and a MRE vertical variable stiffness isolator, as shown in figure 3. In order to avoid vibration of the magnetic excitation component, the magnetic yokes and the coil are suspended above the vibration platform through a steel frame. The measurement system in the experiment consists of accelerometers and data acquisition systems (DAS), as shown in figure 4 ~ figure 6.

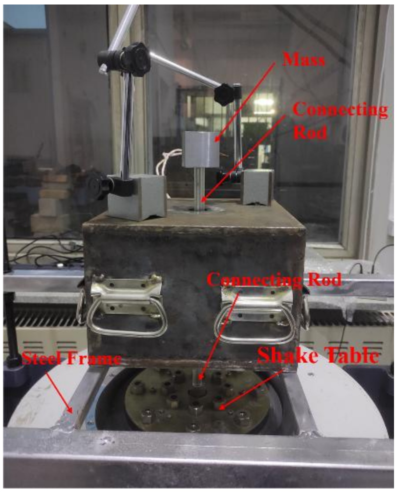


Figure 3: The photo of the tested SDOF system

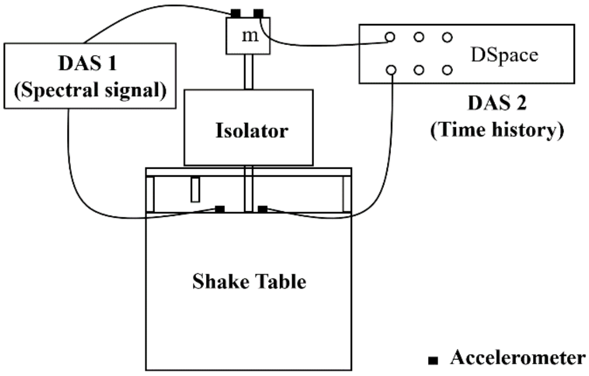


Figure 4: Schematic diagram of measurement system

Figure 5: The piezoelectric accelerometer

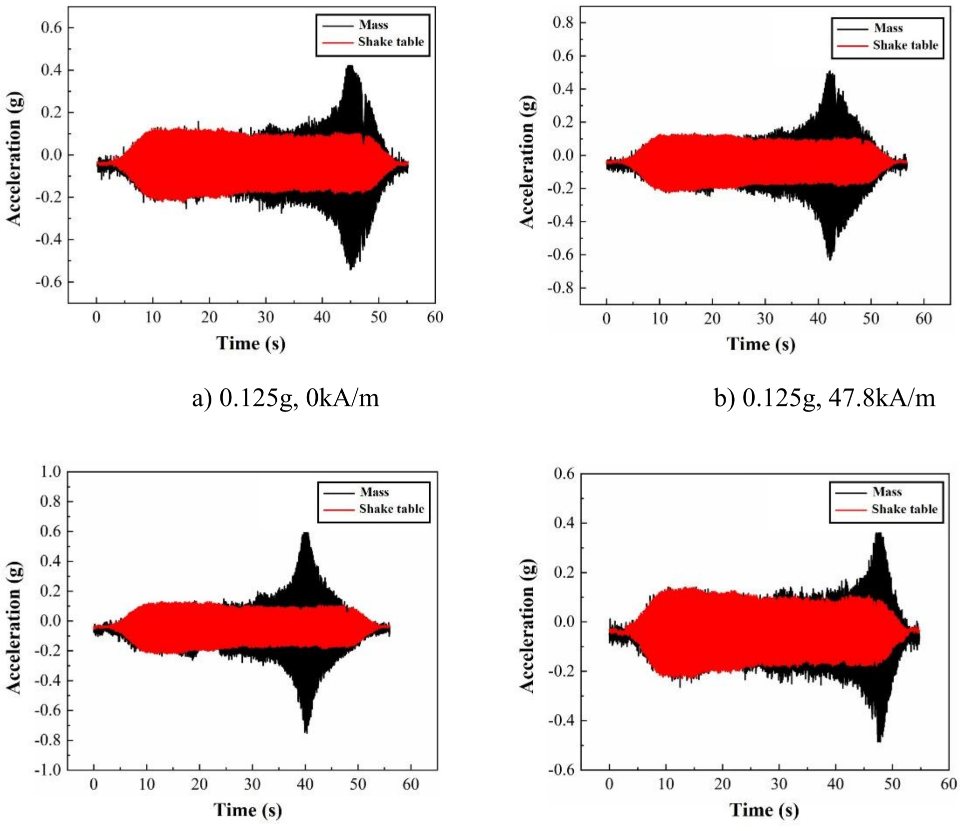
Figure 6: The DSpace (DAS 2)

Two types of loadings, including sweep frequency cases and start-up case, were applied to the SDOF system. Firstly, by applying sweep frequency loading with the acceleration amplitude of 0.125g and various magnetic intensity (0kA/m, 47.8kA/m, 95.1kA/m, and 134.9kA/m), transmission ratios of the isolated system can be obtained as the theoretical basis of the semi-active control algorithm. Applying the algorithm, vertical isolation performance tests of the start-up condition were then carried out to compare the control efficiency between the passive and semi-active cases.

4 RESULTS AND DISCUSSION

4.1 The sweep frequency cases

The frequency sweep test adopted a logarithmic scanning method, with a frequency range of 5Hz to 50Hz and a scanning rate of 3cot/min. The acceleration time history of the mass and shake table under various magnetic intensity and 0.125g shake table accleration amplitude were shown in figure 7a ~ 7d. It can be seen in figure 7a ~ 7d that the acceleration difference between shake table and the mass was relatively small in the beginning. As time increases, the acceleration of the mass block gradually increases until it reaches its peak and then decreases. Meanwhile, it is also shown that the resonance point of the SDOF system gradually moved backward and the amplitude of resonance decreased with the increase of magnetic field intensity.



a) 0.125g, 0kA/m

b) 0.125g, 47.8kA/m

c) 0.125g, 95.1kA/m

d) 0.125g, 134.9kA/m

Figure 7: The time history of acceleration

The spectural signal of acceleration is measured by DAS 1, thus the transmission ratio (TR) curve can be obtained, as shown in Figure 8. It can be seen that TR showed a trend of increasing first and then decreased. For the 0kA/m case, when the input load frequency reached around 20Hz, TR reached its peak, and the SDOF system resonated. By comparing TR-f curves under various magnetic field intensity, it is concluded that the maximum relative change in natural frequency reached 58% because of the MR effect. Moreover, the increase in magnetic field intensity also led to a decrease in the peak value of TR, indicating that the damping ratio of the SDOF system increased with the magnetic field intensity change.

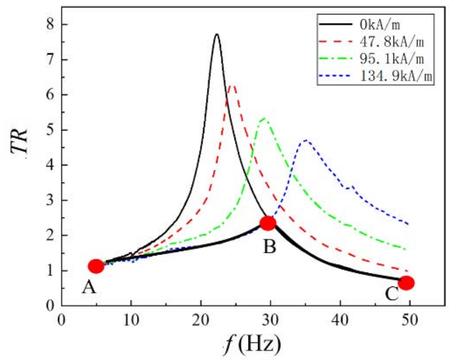


Figure 8: The TR-f curves under various magnetic field intensity

Based on the above results, for the equipment start-up process, the MRE vertical isolation system can adopt the following semi-active control strategy. The excitation voltage is firstly set to its maximum in stage AB. When the loading frequency increases to point B, the power supply voltage is tuned to 0. Applying the proposed strategy, TR of the semi-active SDOF system can be set to the bold line in Figure 8. With the strategy, the peak dynamic response of the structure can be effectively reduced, and the excellent performance of passive control in high-frequency band can be retained as well.

4.2 The start-up cases

To explore the actual performance of the proposed semi-active control strategy, start-up cases were applied to both the passive controlled (0kA/m) and semi-active controlled SDOF system. Figure 9 shows the mass acceleration time history comparison between two control strategies. It can be seen that the peak acceleration response with semi-active control appeared earlier and the amplitude significantly decreased. As a result, the peak values show a decrease of 24% compared to the passive case. However, it is also worth noting that the peak acceleration response of semi-active control is slightly greater than that of passive control at the tuning frequency. It is because the instantaneous stiffness change caused a release of potential energy and led to an impact on the mass above.

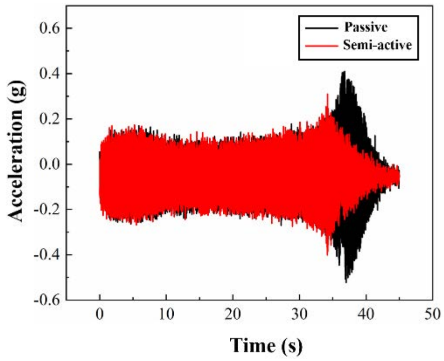


Figure 9: The start-up mass acceleration time history comparison

5 CONCLUSIONS

This paper designed a semi-active MRE vertical isolation system for equipments installed in building, then derived the mechanical model of MRE vertical isolators. After that, the vertical isolation performance tests were carried out to validate the effectiveness of the semi-active isolation system. The conclusions can be drawn as follows:

(1) For sweep frequency cases, the mass acceleration reaches its peak at a certain moment. With the increase of magnetic field intensity, the resonant point will move backwards, and the peak amplitude will decrease.

(2) The semi-active control strategy is proposed applying maximum excitation voltage in stage AB and 0V in BC stage. With the strategy, the response of the structure can be effectively reduced, and the excellent performance of passive control can be retained as well.

(3) Compared to passive control, the proposed semi-active strategy can reduce the mass acceleration amplitude by 24%. Therefore, the excellent performance of the semi-active MRE vertical isolation system is validated.

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