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Abstract

Magnetorheological elastomer (MRE) is known for its field-sensitive shear modulus and damping property when it is exposed to a magnetic field. It has a great potential for the development of vibration reduction devices. Many research, mostly in mechanical engineering, have been focused on different kinds of vibration absorbers and vibration isolators, however few research addresses its potential in base isolation system in civil engineering application. The objective of this paper is to pilot the design and experimental testing of a novel device, an adaptive MRE base isolator, for the development of smart base isolation system. A large-scale design of the novel device with unique laminated structure of steel and MR elastomer layers is adopted. Detailed procedures on designing such adaptive base isolator are introduced. An innovative design on the magnetic circuit, with aim to provide strong and uniform magnetic field to the multi-layer MREs, is proposed to incorporate into the device design. Experimental investigation is conducted to examine its behavior under various cycling loadings when it is applied with different current inputs. Experimental results indicated that the force increase and the stiffness increase of the novel device are about 45% and 37%, respectively. To conclude, the MR elastomer base isolator will be a promising candidate to facilitate the development of adaptive base isolation system for civil structures.

Keywords

testing, adaptive, design, magneto, experimental, rheological, elastomer, base, isolator

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Design and Experimental Testing of an Adaptive Magneto-Rheological Elastomer Base Isolator*

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Abstract— Magnetorheological elastomer (MRE) is known for its field-sensitive shear modulus and damping property when it is exposed to a magnetic field. It has a great potential for the development of vibration reduction devices. Many research, mostly in mechanical engineering, have been focused on different kinds of vibration absorbers and vibration isolators, however few research addresses its potential in base isolation system in civil engineering application. The objective of this paper is to pilot the design and experimental testing of a novel device, an adaptive MRE base isolator, for the development of smart base isolation system. A large-scale design of the novel device with unique laminated structure of steel and MR elastomer layers is adopted. Detailed procedures on designing such adaptive base isolator are introduced. An innovative design on the magnetic circuit, with aim to provide strong and uniform magnetic field to the multi-layer MREs, is proposed to incorporate into the device design. Experimental investigation is conducted to examine its behavior under various cycling loadings when it is applied with different current inputs. Experimental results indicated that the force increase and the stiffness increase of the novel device are about 45% and 37%, respectively. To conclude, the MR elastomer base isolator will be a promising candidate to facilitate the development of adaptive base isolation system for civil structures.

I. INTRODUCTION

Base isolation systems are the most widely implemented technique world-widely for the seismic protection of civil structures [1-2]. When earthquake comes, the base isolation system will decouple external vibrations by isolating destructive frequency contents from transmitting into the main structure above thus maintain the integrity and safety of the structure and contents therein[3]. However, current base isolation systems are mostly passive and are only effective in a narrow band of frequency range. Particularly, the vulnerability for current base isolation practice during far-source and near-source earthquakes becomes a great concern [4]. A new smart material, Magnetorheological (MR) elastomer, promises a solution for overcoming these challenges by developing an adaptive base isolator.

MR elastomer consists of natural or synthetic rubber matrix interspersed with micron sized (typically 3 to 5

microns) ferromagnetic particles [5]. Similar as MR fluids, MR elastomers possess magnetic field-sensitive shear modulus and damping which can be controlled by external magnetic field. Under magnetic field, the material switches from rubber-like property into solid material. After removing the magnetic field, it regains its original state as a rubber. Notably, this process is instant, reversible and repeatable. Due to these attractive features, MRE has received a great deal of attention to be used in the development of vibration isolators and vibration absorbers [6-7]. However, for most of the proposed MRE devices, only few layers of MREs were used due to the difficulty in providing sufficient and uniform magnetic field to multi-layer MREs. For a large-scale MRE device, multi-layers MREs with considerable large diameter are inevitably required, which create even greater obstacle for the magnetic field generation. Therefore, the application of MRE devices to large scale structures remains unsolved, hindering the progress on MRE research till now.

The main purpose of this paper is to develop a large-scale adaptive base isolator utilizing MREs. The novel device consists 47 layers of laminated MREs and steel sheets to achieve the flexible shear stiffness in horizontal direction and sufficient load-carrying ability in the longitudinal direction. An innovative magnetic circuit design was adopted in this design to resolve the challenge in providing sufficient and uniform magnetic field. Detailed procedures are introduced in the second section. Experimental testing was conducted to examine the device performance under various sinusoidal excitations and magnetic fields.

II. DESIGN OF THE ADAPTIVE MAGNETORHEOLOGICAL ELASTOMER BASE ISOLATOR

A. Magnetorheological Elastomer

The materials used for the MREs in this investigation are: silicone rubber (Selleys Pty. LTD), silicone oil, type 378364 (Sigma-Aldrich Pty. LTD) and carbonyl iron particles, type C3518 (Sigma-Aldrich Pty. LTD). The density of silicone rubber, silicone oil and carbonyl iron particles are 1.04 g/cm³, 0.96 g/ml and 7.86 g/cm³, respectively. The diameters of the iron particles are between 3 μ m and 5 μ m. For a 100 g MRE sample, it contains is 10 g silicone oil, 20 g silicone rubber and 70 g carbonyl iron particles. Hence, the volume fraction of the iron powder in the MRE is 30%. The mixture was put into a vacuum case to remove the air bubbles inside it, and then the mixture was poured into a mold for curing under constant magnetic field of 1.0T. The curing time for MRE sample is 24 hours.

Figure 1 shows the strain-stress curve of the normal MRE material in shear mode under various magnetic field strength. The MRE is a soft rubber-like material with 100% shear

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modulus change under the magnetic field of 0.7 Tesla, compared with that with absence of magnetic field. For 10% shear strain, the shear moduli are 0.1MPa and 0.2MPa with magnetic field of 0Tesla and 0.7 Tesla, respectively.

As can be seen in Figures 1, shear moduli of the MRE sample displays an increasing trend with magnetic field, which proves that the MRE exhibits obvious MR effects. Within yield shear strain of MRE, the shear stress and the shear strain exhibit a linear relationship for any given magnetic field. Beyond this critical strain, MRE material displays typical plasticity. The shear yield stress of MRE increases with increase of the applied magnetic field, demonstrating typical MR effects. Beyond the critical shear strain, the MRE behaves as plastic material. For the MRE sample, the shear yield stress varies from 18kPa to 40kPa while the critical shear strains are around 19% to 27% when magnetic field intensity increases from 0T to 0.7 T.

Figure 1. Shear stress vs shear strain at different magnetic fields for MRE

B. Adaptive Base Isolator Design

The configuration of the novel MRE seismic isolators, as shown in Figure 2, incorporates the laminated structural design of traditional laminated rubber bearing [1-3]. It consists of multilayer thin MRE sheets bonded onto multilayer thin steel plates. The advantage for the laminated structure is for its large capability to carry heavy load in vertical direction. The steel plates provide the vertical load capacity and stiffness, and prevent lateral bulging of the rubber. Horizontal flexibility is provided by the shearing deformability of MR elastomer sheets which can be varied instantly under applied magnetic field. In the prototypes, coils are placed outside of the laminated bearing element to provide strong magnetic field to the field-dependent MRE materials. The solenoid coil is made of copper wire and thin non-magnetic support as illustrated in Figure 2. To further enhance the magnetic field in the isolator, a cylindrical steel yoke is designed and installed around the coil to form an enclosed magnetic circuit. To enable movement of the device, a small gap of 5mm between the top plate and the steel yoke is allowed. Detailed design of the MRE seismic isolator can be referred to references [8-9].

In the design of the adaptive seismic isolator, two design parameters are crucial to both practical implementation and theoretical evaluation of its performances, i.e. vertical loading carrying capacity and lateral stiffness of the seismic isolator.

The weight capacity of the laminated base isolator is considered by the following calculation:

Figure 2. Cross section of the MR elastomer base isolator

$$W = A'GS\gamma_w \quad (1)$$

Where, A' is the overlap of the top and bottom of the base isolator, named as the effective area, G is the shear modulus of the rubber, S is the shape factor of a single layer of rubber; γ_w is the allowable shear strain due to weight.

The shape factor S is a non-dimensional measure of the aspect ratio of the single layer of the elastomer, defined as:

$$S = \frac{A_{load}}{A_{load-free}} \quad (2)$$

Where, A_{load} is the area of the base isolator with load applied on, $A_{load-free}$ is the area of the base isolator without any load applied on.

For example, the shape factor S for a rectangular isolator is:

$$S = \frac{L \times B}{2(L+B)t} \quad (3)$$

Where, L and B are the plan dimensions of a rectangular isolator, $L \leq B$, t is the thickness of a single layer rubber.

So, in a square plate of width a with a single-layer thickness t the shape factor is,

$$S = \frac{a}{4t} \quad (4)$$

For a circular plate of diameter Φ and thickness of t , the shape factor is,

$$S = \frac{\Phi}{4t} \quad (5)$$

Figure 3. Effective area of the base isolator under maximum displacement

To analyze performance of a laminated base isolator, the isolator is usually approximated as a vertical shear beam, since the stiff steel layers severely inhibit flexural

deformation while providing no impediment to shear deformation. Therefore, the horizontal stiffness is simplified as:

$$K_b = \frac{GA}{h} \quad (6)$$

Where, A is the rubber layer area (full cross section area), h is the total thickness of the rubber layer.

From (6) it is clear that in design low lateral stiffness can be achieved by decreasing the cross section area of the laminated structure or by increasing the thickness of the rubber layers. However, if the cross sectional area is not sufficient or the rubber layer is too thick, the isolator may become unstable when it is subject to sever vibrations while supporting a large vertical loading. Therefore, an optimization of these two parameters must be considered in the design process to retain the stability of the base isolator while maximize the performance of the isolator.

C. Device Assembly

In this prototype device design, there are 46 layers of the steel sheet with thickness of 1 mm and 47 layers of MR elastomer sheets with thickness of 2 mm. The diameter of the MR elastomer and steel sheets is 140 mm. The bonding between the steel and MRE layers were realized through the utilization of powerful super glue. As an innovative design in the prototype, an electromagnetic coil is placed outside of the laminated elastomer structure. A cylindrical shape non-magnetic support, firmly attached outside of the coil, is made of epoxy material. The total winding number of the coil is 3100 turns. The diameter of the coil wire is 1.2 mm and the total length of the wire is 2100m. The wire is made of copper and the resistance of the coil is 32.3 Ω . The space between the laminated MR elastomer structure and the coil enables the isolator to have a free lateral motion at a maximum deformation of 26 mm, equivalent to the maximum allowable shear strain of 27.7%. To enable the lateral motion of the device, there is also a small gap, 5mm, between the top plate and the steel yoke.

Figure 4. The laminated MR elastomer and steel structure

D. Innovative Magnetic Circuit

As known, the magnetic conductivity of the MR elastomer is fairly low and hence it is difficult to achieve saturated magnetic field for MR elastomer material inside the coil. Traditional combination of steel layers embedded in-between MR elastomer layers, fortunately, ensures the high magnetic conductivity of the base isolator. After investigation on the magnetic field distribution in the solenoid [8], an innovative magnetic circuit design is used in the proposed device. In the

magnetic circuit design, two solid steel cylinders with identical dimension are added on the top and bottom of the laminated structure to further improve the permeability of the magnetic core. Hence, the magnetic core for this design is consisted of the two steel cylinders and the laminated MRE and steel structure. To form an enclosed path for the magnetic flux, two steel plates, one on the top and the other on the bottom, are designed to perform two roles as: 1) creating paths for magnetic field and 2) being fixture to connect the device to the ground and the superstructure above. In addition, a circular steel yoke is firmly placed outside of the coil to complete the magnetic flux path. With this design, a uniform magnetic field of 0.3T can be achieved, as shown in Figure 5.

Figure 5. Magnetic field measurements

III. EXPERIMENTAL TESTING

A. Experimental Setup

In the experimental set-up, as shown in Figures 6 and 7, the shake table is used to provide horizontal motions to the isolators either in a quasi-static mode or in a dynamic mode. The MR elastomer base isolator is mounted on the shake table and its base will move along with the shake table motion. Load cell is installed to connect the MRE base isolator and a fixed reaction rig outside of the table to measure the lateral load applied to the isolators. During testing, the top plate of the MRE base isolator and the load cell remain still thus eliminate the undesired forces that may be induced by the motion of top plate. A DC power supply with capacity of 200V and 8A provides DC current to the magnetic coil. During dynamic testing a series of harmonic waveforms at frequencies of 0.5Hz, 1.0Hz and 3.0Hz, were produced by the shake table to evaluate the behavior of the MR elastomer base isolator. The amplitudes of the input motion from the shake table were 5mm and 10mm. During the tests, the MR elastomer base isolator was energized with various currents at 0.0A, 3.0A and 5.0A, respectively.

Figure 6. Sketch map of the experimental set-up

Figure 7. Shake table testing

B. Testing Results

Figure 8 shows the typical force response of the MR elastomer base isolator at the amplitude of 5mm and a constant loading frequency of 0.5Hz for various applied currents, i.e. 0.0A, 3.0A and 5.0A. The shake table motion is also plotted in the figure. As can be seen, there is significant increase of the force produced from the MR elastomer base isolator when increase the applied current from 0.0A to 5.0A. The force-displacement loops of the MR elastomer base isolator at amplitude of 5mm and 10mm are also shown in Figure 9 and 10, respectively.

TABLE 1. MAXIMUM FORCE [N] OF THE MR ELASTOMER BASE ISOLATOR UNDER VARIOUS LOADING CONDITIONS

Amplitude D=5mm					Amplitude D=10mm				
Frequency [Hz]	Applied current [A]			Increase %	Frequency [Hz]	Applied current [A]			Increase %
	0.0	3.0	5.0			0.0	3.0	5.0	
0.5	102.05	117.12	148.29	45.31	0.5	198.65	224.54	271.53	36.68
1.0	107.13	124.08	154.76	44.46	1.0	214.47	235.11	286.77	33.71
3.0	122.65	142.96	175.32	42.94	3.0	246.06	270.49	327.64	33.15

TABLE 2. EFFECTIVE STIFFNESS [kN/M] OF THE MR ELASTOMER BASE ISOLATOR UNDER VARIOUS LOADING CONDITIONS

Amplitude D=5mm					Amplitude D=10mm				
Frequency [Hz]	Applied current [A]			Increase %	Frequency [Hz]	Applied current [A]			Increase %
	0.0	3.0	5.0			0.0	3.0	5.0	
0.5	19.73	22.24	27.13	37.49	0.5	18.58	21.62	25.59	37.75
1.0	20.91	23.61	28.59	36.72	1.0	19.53	22.77	26.92	37.83
3.0	24.22	27.38	32.51	34.27	3.0	23.42	26.03	30.40	29.80

TABLE 3 DAMPING COEFFICIENT [kN*s/M] OF THE MR ELASTOMER BASE ISOLATOR UNDER VARIOUS LOADING CONDITIONS

Amplitude D=5mm				Amplitude D=10mm			
Frequency [Hz]	Applied current [A]			Frequency [Hz]	Applied current [A]		
	0.0	3.0	5.0		0.0	3.0	5.0
0.5	0.98	1.23	1.55	0.5	1.07	1.25	1.55
1.0	0.56	0.69	0.87	1.0	0.63	0.68	0.86
3.0	0.24	0.29	0.37	3.0	0.24	0.29	0.36

Figure 8. Typical force response of the MR elastomer base isolator at d=5mm and f=0.5Hz

The maximum force, effective stiffness and damping coefficient are listed in Table1-3. The methods to calculate the effective stiffness and damping coefficients can be found in [9]. The force increase for each testing set varies from 33% to 45%. For a given frequency at the constant amplitude of 5mm, the stiffness increases vary from over 34% to 37%. While for the amplitude of 10mm, the stiffness increases is from about 30% to 37%. When the loading frequency increases, the stiffness increase decreases. It is interesting to observe that, for two different loading amplitudes with same loading frequency and same input current, the effective damping coefficients, remain nearly the same. The values of damping coefficient for low loading frequency are higher than that under higher loading frequency.

Figure 9. Force-displacement loops of the MR elastomer base isolator at amplitude of 5mm and frequency of 0.5Hz.

The maximum forces at the amplitude of 5mm are shown in Figure 11. For a given input with 5mm amplitude and 0.5 Hz frequency, the maximum force generated by MRE seismic isolator increases from 102N (off-state, $I=0.0A$) to 148N ($I=5.0A$), equivalent to more than 45% increase. As it can be seen, under applied magnetic field, increase of the force can vary from 33% up to 45% for the MRE seismic isolator for any given sinusoidal input. It is shown that the maximum forces of the device exhibit a linear relationship with the applied currents.

Figure 10. Force-displacement loops of the MRE base isolator at amplitude of 10mm and frequency of 1.0Hz.

Figure 12 shows the variation of effective stiffness versus various magnetic field strengths, indicated by the applied

currents in the figure. For different loading frequencies, the relationship between the effective stiffness and applied currents remains similar. However, the effective stiffness increases dramatically with increase of the applied currents with a nonlinear trend. The relative increase for a given loading frequency is around 36% when the applied currents vary from 0.0A to 5.0A.

Figure 11. Maximum force of the MRE seismic isolator along various applied currents

Figure 12. Effective stiffness of the MRE seismic isolator along various applied currents

To sum up, based on the previous analysis discussion, it can be further concluded that the MR elastomer base isolator, exhibited visco-elastic behaviours, can be used as a controllable stiffness device, with stiffness increase up to 30% to 38% for various loading conditions. The damping in the MR elastomer device is relatively low without magnetic field but increase with application of magnetic field. For ex-ample damping ratio can change from 0.24 kN*m/s when the loading frequency is 3.0Hz and (no field at the loading frequency is 3.0Hz) is applied to 1.55 kN*m/s when (5.0A current input at the loading frequency is 0.5Hz) with 5.0A current input.

Capable of instantly changing its shear stiffness and damping property, by altering the applied currents, the proposed MRE base isolator is able to introduce a considerable adaptability into the base isolator and thus can

overcome the shortcomings associated with traditional passive base isolators [10-11].

IV. CONCLUSIONS

In this paper, a novel adaptive base isolator was successfully designed and prototyped utilizing MR elastomer. The proposed MR elastomer base isolator contains unique structure as multi-layer laminated steel and MR elastomer to suit for civil engineering applications. Provision of a uniform 0.3 T magnetic field was achieved through an innovative magnetic circuit design which includes a magnetic core (MRE laminated structure, two steel blocks) and an enclosed yoke to increase the magnetic permeability. The behaviors of the MR elastomer base isolator were experimentally tested and results were analyzed through two important measures, i.e. effective stiffness and damping. The increases on force, effective stiffness and equivalent damping were obtained through the experimental data. It is shown that the force increase of the MRE base isolator is up to 45% and the stiffness increase of the MRE base isolator is up to 38%. With instant controllable stiffness and damping property, the proposed novel device has great potential in the base isolation system for civil structure and is able to resolve the challenge facing the base isolation system.

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