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MRE Properties under Shear and Squeeze Modes and Applications

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ABSTRACT: Magnetorheological elastomers (MREs) are smart materials whose mechanical properties, like their modulus and elasticity, can be controlled by an external magnetic field. This feature has resulted in a number of novel applications, such as adaptive tuned dynamic vibration absorbers for suppressing unwanted vibrations over a wide frequency range. MRE-based devices operate in different modes, such as shear mode and squeeze mode; however, the study of mechanical performances of MREs under squeeze mode is very rare. This article aims to investigate MRE performances under both shear and squeeze modes. Experimental studies and simulations were conducted to analyze the MR effect in both modes. These studies indicate a different working frequency ranges for both modes. In a case study, a MRE-based vibration absorber was built up in a simulation and its mechanical performances were analyzed, which demonstrated good capabilities in reducing vibrations.

Key Words: magnetorheological elastomers, shear and squeeze mode, adaptive tuned dynamic vibration absorber.

INTRODUCTION

MAGNETORHEOLOGICAL elastomers (MREs) are composite materials of a rubber-like base, micron-sized magnetizable particles, and additives (Carlson and Jolly, 2000; Bellan and Bossis, 2002; Lokander and Stenberg 2003; Chen et al., 2007; Stepanov et al., 2007; Zhang et al., 2008). When individual particles are exposed to an applied magnetic field, magnetic dipole moments pointing along the magnetic field are induced in the particles. Pairs of particles then form head-to-tail chains. After the matrix is cured, the particles are locked into place and the chains are firmly embedded in the matrix. The elastic modulus of MREs increases steadily as the magnetic field increases. By removing the magnetic field, MR elastomers immediately reverse to their initial status. A few groups made use of such materials to develop novel adaptive tuned dynamic vibration absorbers, as such MRE-based vibration absorbers are expected to have many advantages: very fast response (less than a few milliseconds), simple structure, easy implementation, good maintenance, high stability, and effective control. Ginder et al. (2002) did a pioneer work that utilized MREs as variable-spring-rate elements to develop an adaptive tuned dynamic vibration absorber (ADTVA). Their results indicated that a natural frequency ranged from 580 to 710 Hz at a magnetic field 0.56 T. However, the natural frequency varying was only 22% from its center frequency. Deng et al. (2006) developed MRE ATDVA whose natural frequency can be tuned from 55 to 82 Hz. Its absorption capacity was also experimentally justified. Similar MRE vibration absorber was developed by Zhang and Li (2009). Experimental results indicated that the absorber can change its natural frequency from 35 to 90 Hz, 150% of its basic natural frequency. It is noted that the abovementioned MRE dynamic vibration absorbers do not have wide enough tuning frequency ranges. The reason for this could be because the MRE materials operate in a simple shear mode. In MR fluid research, a few groups (Zhang et al., 2004; Tang et al., 2006; Li and Zhang, 2008) demonstrated that MR fluid working in a squeeze mode would greatly enhance their MR effects. In this study, we would extend this idea to the MR elastomer research. In other words, this study aims to investigate the MR effect under squeeze mode and compare it with that of shear mode. MRE samples with different compositions were fabricated and tested on a home-made test rig. The mechanical performances under both shear mode and squeeze mode were used to verify simulation analyses based on a one degree of freedom model. This study is expected to provide good guidance to develop high-efficiency MRE-based devices.

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FABRICATION AND CHARACTERIZATION OF MR ELASTOMERS

Fabrication of MRE Samples

In this study, four MRE samples with different compositions were manufactured. Five components, including two types of silicon rubber, a silicon oil, a curing agent, and two types of iron particles, were used to fabricate these MRE samples. The mass fractions are listed in Table 1. The silicon rubber, PDMS 2025 (Dow Corning Corporation, USA), was used for MRE 1 and MRE 2, while a room temperature vulcanizing silicon sealant (PERFIX, Selleys Pty Ltd, Australia) was used for fabrication of MRE 3 and MRE 4. A silicon oil DC 200/200cs (Dow Corning Corporation, USA) was mixed within the sample to change the ductility of the rubber base. To this base two grades of iron powder were added, one with 5 μm sized particles (Sigma-Aldrich Chemie GmbH, Germany) and one with 100 μm (M93-000-31 F14 Neosid Australia Pty Limited).

The mixture was filled in a mold and placed in a strong magnetic field of 1 T generated by an electromagnetism system (Peking EXCEEDLAN Inc., China). Ten minutes later, the magnetic field was reduced to 0.5 T so that the samples were cured for seven more hours. After 24 h the mixture was removed from the mold. Samples with a diameter of 20 mm and a thickness of 6 mm were cut out. With these, MRE tests were curried out and the relative magnetorheological effects as well as the resonance frequency were measured.

Experimental Characterization of MRE Performances

The experiments were conducted on a test rig with two different setups, as shown in Figure 1(a) and (b), where MREs work in squeeze mode and shear mode, respectively.

The test rig was built up as a one degree of freedom system with a mass, connected to the base via two pieces of MREs, and moves independently to the base. In squeeze mode, the MREs and mass were directly fixed on the base by a double-sided adhesive tape. In shear mode the mass was fixed by contact forces of two cylinders which were tightened on the base. On the base two coils were wound to generate a magnetic field which was adjusted by a GW laboratory DC power supply (Type: GPR-3030D, TECPEL CO., Ltd. Taiwan). The magnetic field strength up to 150 ± 17 mT can be obtained when the coil current is 3 A. The base was forced to vibrate by a vibration exciter (Type: JZK-5, Sinocera Piezotronics, Inc. China), which was driven by a signal source from a power amplifier (YE5871-100 W) and a Data Acquisition (DAQ) board (Type: LabVIEW PCI-6221, National Instruments Corporation. USA). During the experiments a frequency range from 35 to 90 Hz was obtained, as shown in Figure 1(c).

Table 1. Component weight ratio of manufactured MREs.

	MRE 1	MRE 2	MRE 3	MRE 4
Silicon rubber	20 wt%	16 wt%	–	–
Silicon sealant	–	–	20 wt%	24 wt%
Silicon oil	20 wt%	24 wt%	20 wt%	16 wt%
Iron particle (5 μm)	20 wt%	20 wt%	60 wt%	60 wt%
Iron particle (100 μm)	40 wt%	40 wt%	–	–

Two acceleration sensors (Type: CA-YD-106) were placed on the upper surface of the mass and the base to measure the amplitude and the phase angle between both parts. The tramsmissivity amplitude responses of the tested MRE with variable magnetic field intensities are shown in Figure 1(c). The resonance frequency of the mass was located at the maximal amplitude of the oscillation and the relative MR effect was calculated by the increase of the frequency at different magnetic field strengths. The results of preliminary tests of the four manufactured MREs in shear mode are listed in Table 2.

It can be seen from Table 2 that the resonance frequencies increase steadily with the increment of magnetic field, which demonstrated the MR effects. It is also noted that the relative MR effects for these four MRE samples are very different. The MR effects of samples 1 and 2 have a lower level, while samples 3 and 4 show a higher change in frequency. For example, the MR effect of sample 4 is more than 15 times higher than of sample 1. The major composition difference between sample 1 and 2 against sample 3 and 4 is the particle size. As shown in Table 1, for samples 1 and 2 the mixture with particles of 5 and 100 μm were used while for samples 3 and 4 only particles of 5 μm were added. Besides, the components used for the rubber base, comparing MRE 1 and 2 against MRE 3 and 4, also have an influence of the MR effect.

Similarly, the MRE performances under squeeze mode were experimentally evaluated. For the MRE sample 3, the performance comparison between shear mode and squeeze mode is shown in Table 3. In addition, the comparison between experimental results and modeling predictions, which will be detailed in the section 'Comparison between Theoretical Analysis and Experimental Results', are also listed in this table. As can be found from this table, the overall difference between the experimental results and modeling predictions is about 12%. Further inspection of the two cases of minimum and maximum magnetic fields indicates that the difference is much small. For example, the natural frequency at 0 mT has about 4% difference (25–26 Hz) while at 108 mT has less than 2% difference (52–53 Hz).

The tests using MRE 3 in shear and squeeze mode show different MR effects and a different

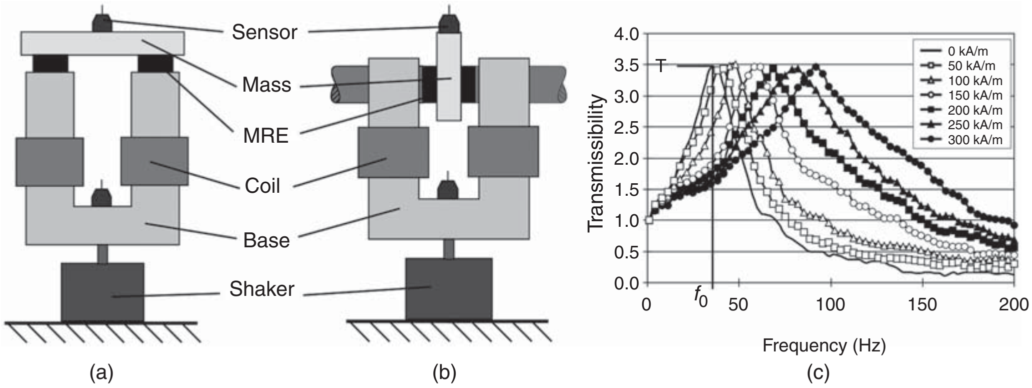

Figure 1. *Experimental setup for measurements in (a) squeeze mode, (b) shear mode, and (c) recorded frequency responses.*

Table 2. ***Measured resonance frequency f_0, amplitude T and MR effect for MREs in shear mode.***

	MRE 1			**MRE 2**			**MRE 3**			**MRE 4**		
Current (A)	**B (mT)**	**T_{max}**	**f_0 (Hz)**	**B (mT)**	**T_{max}**	**f_0 (Hz)**	**B (mT)**	**T_{max}**	**f_0 (Hz)**	**B (mT)**	**T_{max}**	**f_0 (Hz)**
0	0	3.31	65	0	2.89	36	0	2.53	25	0	2.40	26
0.76	45	3.70	66	42	2.96	38	46	2.43	26	51	2.29	32
1.5	81	3.97	67	73	3.17	41	90	2.36	35	91	2.35	40
2.26	113	3.94	72	111	3.08	43	136	2.52	46	131	2.57	52
3	132	4.39	71	143	3.21	43	156	2.69	53	167	2.72	64
Increase		9.2%			19.4%			112.0%			146.2%	

Table 3. ***Comparison of test data and calculated results for MREs in squeeze and shear mode.***

	Measurement						**Calculation**						
	Squeeze mode			**Shear mode**			**Squeeze mode**			**Shear mode**			
Current (A)	**B (mT)**	**f_0 (Hz)**	**T_{max}**	**B (mT)**	**f_0 (Hz)**	**T_{max}**	**f_0 (Hz)**	**G' (f_0) (Pa)**	**T_{max}**	**f_0 (Hz)**	**G' (f_0) (Pa)**	**T_{max}**	**Shear strain (%)**
0	0	48	2.68	0	25	2.53	47	60.1e3	2.13	26	56.3e3	2.31	10
0.76	46	53	2.77	32	26	2.43	50	66.1e3	2.10	27	61.8e3	2.27	10
1.5	90	63	3.26	49	35	2.36	60	95.7e3	2.27	34	90.2e3	2.49	5
2.26	136	76	3.66	76	46	2.52	73	143e3	2.50	41	136e3	2.71	2
3	155	85	3.66	108	53	2.69	83	186e3	2.52	52	216e3	3.04	0.1
		37 Hz			28 Hz			36 Hz			26 Hz		
Increase		77.1%			112.0%			76.6%			100.0%		

working frequency range. The initial resonance frequency in squeeze mode without an applied magnetic field is almost twice as high as in shear mode. Also the absolute changing frequency increment is higher in squeeze mode with 37 Hz than in shear mode with 28 Hz. This indicates that the MR effect is dependent on the working mode of the MRE, which should be considered in developing MRE-based devices.

Characterization of Material Properties using MR Rheometer

The rheomoter Physica MCR301 (MEP instruments, Anton Paar Germany GmbH), as shown in Figure 2, with a parallel-plate configuration was used to measure material properties of MR elastomers. The MRE samples were cut into standard ones with a diameter of 20 mm and a thickness of 1 mm. Each sample was placed in between the plates, and the squeeze force, ranging from 5 to 15 N, were placed to the sample through the upper plate. After which, oscillatory shear was applied to obtain dynamic performances of the samples. In these tests, five strain amplitudes, 0.1%, 1%, 5%, 10%, and 15%, were selected to measure viscoelastic properties of these samples under various magnetic fields.

Viscoelastic properties of MR materials are generally characterized by using the amplitude sweep mode and/or

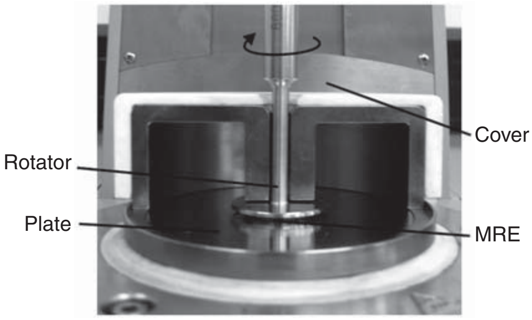

Figure 2. Rheometer setup.

frequency sweep mode (Li et al., 1999). In this study, the frequency sweep mode was used to study the effect of strain amplitude and magnetic field on the viscoelastic properties of MRE samples. At a constant magnetic field of 409 mT, the storage modulus versus frequency at various strain amplitudes was shown in Figure 3.

As can be seen from this figure, the storage modulus initially shows an increasing trend over frequency up to a maximum value. Then it decreases slightly with further increasing frequency. Also, the storage modulus decreases steadily with the increment of the strain amplitude. The effect of magnetic field was measured and shown in Figure 4. As common, the storage modulus increases steadily with the increment of the magnetic field, which demonstrates the MR effect. Again, there is an optimal frequency, in which MRE has the highest storage modulus.

Besides, the frequency dependence of loss factor under various strain amplitudes and magnetic fields are shown in Figures 5 and 6, respectively. The results indicate that the loss factor is indeed amplitude dependent. For strain amplitudes less than 1%, the loss factor lies between 0.2 and 0.4, which agrees well with reports (Demchuk, 2002; Kallio, 2005). However, for high strain ampltidue the loss factor values can be up to 0.9, which demonstrates that MRE have non-linear viscoelastic properties. This behavior was also detected at MR fluids (Li et al., 2003) and will be considered in future studies.

COMPARISON BETWEEN THEORETICAL ANALYSIS AND EXPERIMENTAL RESULTS

Modeling Analysis

The model, to describe the elastomers mathematically, is a one degree of freedom system as shown in Figure 7. Here, k^* is the complex stiffness of MR elastomers and m is the weight of the mass. The weights of the MREs are neglected.

The equation of motion of this system is defined by:

$$m\ddot{x}_1 + k^* x_1 = k^* \hat{x}_e \cdot \sin(\omega t), \tag{1}$$

with the variable excitation $\hat{x}_e \sin(\omega t)$ of the shaker. The stiffness of the MREs is substituted either by a shear spring or a compression spring, according to the used mode. The stiffness in shear mode is dependent on the shear modulus G the square face A and the thickness h of the MRE:

$$k_{\text{shear}} = \frac{G \cdot A}{h}. \tag{2}$$

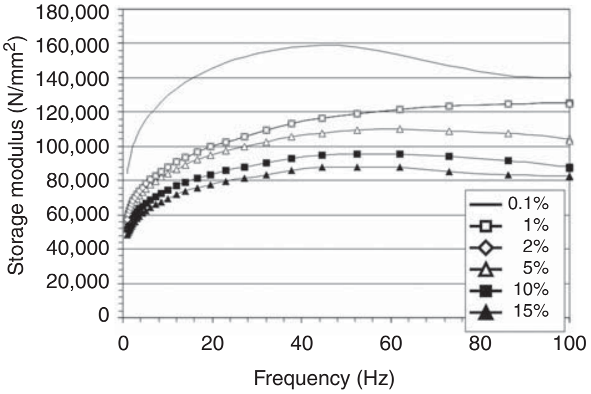

Figure 3. Storage modulus dependent on shear strain at a current intensity of 409 mT.

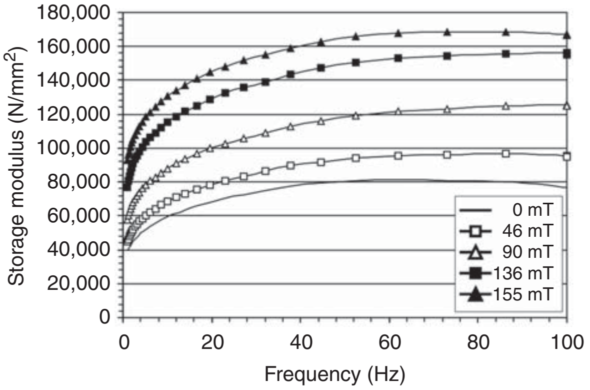

Figure 4. Storage modulus dependent on current intensity at a shear strain value of 1%.

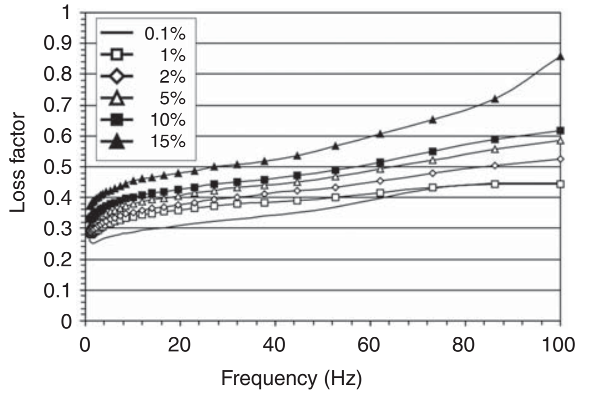

Figure 5. Loss factor dependent on shear strain at a current intensity of 409 mT.

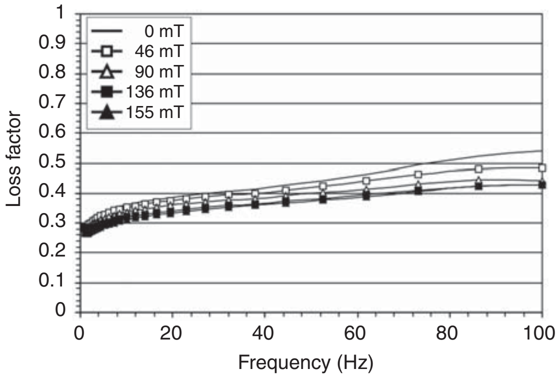

***Figure 6.** Loss factor dependent on current intensity at a shear strain value of 1%.*

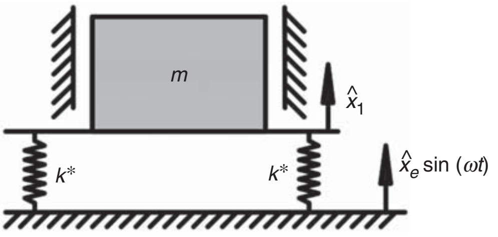

***Figure 7.** Mechanical one degree of freedom model to calculate the system behavior.*

In squeeze mode the MRE acts like a compression spring where its stiffness depends on the Young's modulus E and the length ℓ:

$$k_{\text{squeeze}} = \frac{E \cdot A}{\ell}. \tag{3}$$

Thereby the Young's modulus can be determined by the shear modulus with:

$$G = \frac{E}{2 \cdot (1 + \nu)}. \tag{4}$$

For a rubber-like material the Poisson's ratio ν is set to a constant of 0.5. With this value and $h = \ell$ the stiffness of the compression spring is three times higher than for the sheared spring which indicates higher natural frequencies as already recorded in Table 2. Investigations have shown that the shear modulus for elastomers is complex and has to be expressed by an energy storing part G' and an energy dissipating part η, called loss factor. The general shear modulus is now substituted by the complex one of the MRE:

$$G = G'(1 + i\eta). \tag{5}$$

Including this expression in Equation (3) the complex stiffness of the MRE can now be written as:

$$k^* = \frac{G \cdot A}{h} = \frac{G' \cdot A}{h}(1 + i\eta). \tag{6}$$

By substituting the stiffness in the equation of motion (1) the system is described by:

$$m\ddot{x}_1 + \frac{G' \cdot A}{h}(1 + i\eta)x_1 = \frac{G' \cdot A}{h}(1 + i\eta) \cdot \hat{x}_e \cdot \sin(\omega t). \tag{7}$$

For a mathematical description of the MR behavior the transmissibility T of the one degree of freedom system is of high interest. The transmissibility is defined as the absolute value of the displacement ratio of output and input, and can be calculated for this problem as:

$$T = \left|\frac{\hat{x}_1}{\hat{x}_e}\right| = \sqrt{\frac{1 + \eta_\omega^2}{\left(1 - \dfrac{\omega^2 \cdot m \cdot h}{G'_\omega \cdot A}\right)^2 + \eta_\omega^2}}. \tag{8}$$

Here, the storage modulus G'_ω and loss factor η_ω are dependent on the excitation frequency and were measured by using a MR rheometer, as shown in Figures 3–6. The mass $m = 0.2\,\text{kg}$, the square face $A = 320\,\text{mm}^2$, and the thickness $h = 5.5\,\text{mm}$ of the squeezed MREs have been taken over from the test rig setup.

Comparison and Discussion

By substituting the measured values of the storage modulus and loss factor as well as other parameters into Equation (8), the transmissibility and the resonance frequency f_0 of MRE 3 at various magnetic fields were calculated and listed in Table 3. For both shear mode and squeeze mode, the calculations are very close to the experimental results. Thus, the model analysis is justified.

The resonance frequency in shear and squeeze mode shows an increasing trend with magnetic field, which is due to MR effect. However, the resonance frequency at the squeeze mode is much higher than that in shear mode, because of the different modes the elastomer is subjected to. The results shown in Table 3 demonstrate that the relative MR effect is higher in shear mode than in squeeze mode, whereas the absolute increase of the resonance frequency with 37 Hz is higher in squeeze mode. It is also visible that the highest MR effect obtained in shear mode is about 100%, which might be sufficient for practical applications. The highest MR effect for MR material is dependant on the magnetic saturation (Davis, 1999; Carlson and Jolly, 2000; Nguyen et al., 2007; Stepanov et al., 2007). For an iron particle, the saturation flux density is about 2 T. Unfortunately, we cannot characterize the highest MR effect because of the facility limitation.

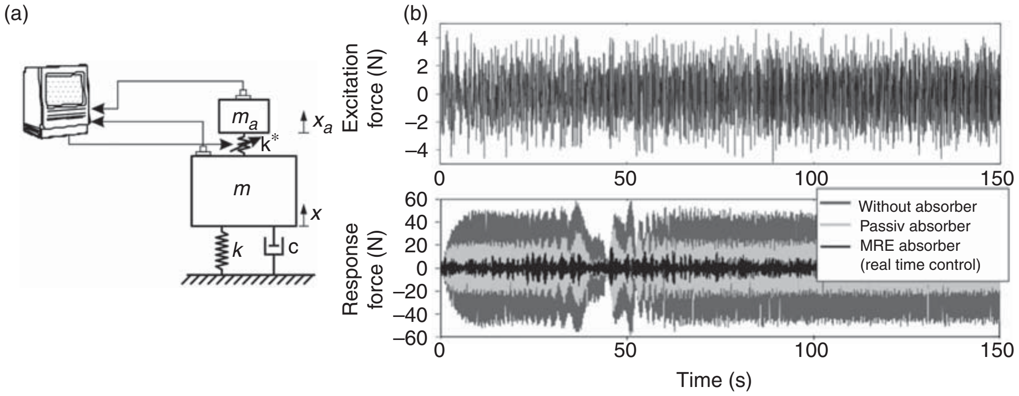

Figure 8. *Mechanical model of an ATDVA (a) and amplitude response for simulated setups (b).*

DEVELOPMENT OF MRE VIBRATION ABSORBER

To verify the efficiency of an adaptive tuned dynamic vibration absorber using MR elastomers in shear mode a simulation was developed with Matlab/Simulink. The mechanical model of the absorber is shown in Figure 8(a). On a mass m which is connected to the base via a spring with stiffness k and a damper with damping factor c, a second mass m_a is mounted. The complex spring between both parts simulates the MRE. In the simulation the mass ratio between m_a and m was set to 0.01. The main mass was excited by a multi disturbance which consisted of three sine sweeping force signals with amplitude 1 and with constant frequencies of 35, 50, and 90 Hz, and two sine sweeping waves with amplitude 1 and varying frequencies from 1 to 200 Hz and 35–90 Hz, respectively. The stiffness of the MRE was adjusted by a real time controller which switched the magnetic current intensity of the coils between 0 A and 2 A and with this the magnetic field strength.

In Figure 8(b) the response signals are shown for the described system without any vibration absorber, with a passive tuned dynamic vibration absorber and with an MRE-based ATDVA. For the system without control the simulation results show large force amplitudes because the excitation is close to its natural frequency. The passive TDVA can suppress the amplitude of the primary system by half while the MRE-based ATDVA using real time control logic can significantly reduce the vibration of the primary system. Thus the MRE-based ATDVA is effective for even low mass ratios. The simulation has shown that MRE-based vibration absorbers are high efficient and with the adjustable frequency range by using the MRE in different modes, they are deployable in a wide application area.

CONCLUSION

In this study, the fabrication of MR elastomers and characterization of their mechanical performances under shear and squeeze mode were presented. The results show an increase of the natural frequency about 28 Hz for squeeze mode and 37 Hz for shear mode. A one degree of freedom model was used to study the MRE performances under both modes. The modeling analysis, in terms of strain and frequency dependence of storage modulus, agreed well with experimental results. The efficiency of a MRE-based vibration absorber was simulated and compared to setups without an absorber and with a passive one. The comparison indicates that the MRE vibration absorber is superior to the other two cases by significantly reducing the responding forces even for low mass ratios.

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