Study on a Dynamic Stiffness-tuning Absorber with Squeeze-strain Enhanced Magnetorheological Elastomer

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ABSTRACT: This article presents the design and analysis of a novel dynamic stiffness tuning vibration absorber working with Magnetorheological elastomers (MRE). In this design, the MRE worked in a shear mode, but its MR effect was significantly enhanced by dynamically squeezing the sample thickness with an embedded piezoelectric (PZT) actuator. With this design, both the quasi-static magnetic field and the PZT driven dynamic squeeze strain in the direction of particles chain were properly adjusted to control the vibration of the primary system. The vibration suppression capabilities were theoretically analyzed by the harmonic analysis. A combined control strategy (the tuning strategy and the ON–OFF strategy) and the control system were developed to suppress the vibration of the primary system. The simulation results indicate that the proposed MRE-PZT-based dynamic stiffness-tuning dynamic vibration absorber (DSTDVA) exhibits more effective suppression capabilities than those conventional MRE-based quasi-static tuned vibration absorbers; the stronger the enhanced effect of squeeze strain on MRE's shear storage modulus is, the more effective vibration suppression capabilities the proposed MRE-PZT-based DSTDVA has.

Key Words: Magnetorheological Elastomer, Vibration absorbers.

INTRODUCTION

Vibration absorbers, discovered one century ago, have been proved to be an effective way to suppress unwanted vibrations at a narrow frequency range (Frahm, 1909). Adaptive tuned vibration absorbers (ATVAs) expand the effective band and greatly improve their performances in many applications by adjusting their nature frequencies properly to compensate for the drift in the excitation frequency (Walsh and Lamancusa, 1992; Flotow et al., 1994; Franchek et al., 1996; Brennan, 1998; Flatau et al., 1998; Williams et al., 1999; Davis and Lesieutre, 2000; Nader and Behrooz, 2002). As a new kind of smart material, the modulus of Magnetorheological Elastomers (MREs) can be controlled by applying an external magnetic field rapidly, continuously, and reversibly (Shiga et al., 1995; Ginder et al., 1999; Carlson and Jolly, 2000; Bellan and Bossis, 2002). This characteristic makes MRE competent to work as a smart spring element of ATVA (Ginder et al., 2001; Deng and Gong, 2007; Lerner and Cunefare, 2008).

It is noted that the conventional MRE-based ATVAs are mainly quasi-static tuned vibration absorbers. The ATVA nature frequency is adjusted properly to compensate for the drift in the excitation frequency and keeps unchanged until the excitation frequency varies. In this way, the vibration absorption capacity greatly decays as the damping of ATVAs increases, which definitely limits their applications (Sun et al., 2006). To overcome this shortcoming, a new design of MRE-based dynamic stiffness-tuning dynamic vibration absorber (DSTDVA) was proposed in this study. The MRE in the proposed design still works in a shear mode, similar to conventional MRE ATVAs. However, the design consists of a PZT component, which is embedded in a closed C-shape magnetic circuit for controlling the squeeze strain in the direction of particles chain. Both the magnetic field, generated by the magnetic circuit, and the dynamic squeeze strain in the direction of particles chain can be adjusted to control the vibration of the primary system.

This article is split into five sections. Following the introduction section, the enhanced effect of squeeze strain on shear storage modulus will be presented in 'The Enhanced Effect of Squeeze Strain on Shear Storage Modulus' section. The conceptual design of a DSTDVA, its working mechanism as well as its theoretical analysis will be described in 'The Mechanical structure and working principle of DSTDVA' section. The control system, control strategy and its vibration

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Figures 1–5 and 7–11 appear in color online: http://jim.sagepub.com

1045-389X/09/10 1195–8 $10.00/0 DOI: 10.1177/1045389X09104790

Los Angeles, London, New Delhi and Singapore

suppression capacity are shown in the 'Study of the Vibration Suppression Capacity of the proposed DSTDVA' section. The conclusions will be summarized in the final section.

THE ENHANCED EFFECT OF SQUEEZE STRAIN ON SHEAR STORAGE MODULUS

The MRE samples consist of silicone rubber as a matrix, additives, and carbonyl iron particles with the size of 3–5 µm. First, all the ingredients were thoroughly mixed, compressed into a mold and placed into the magnetic excitation device. Then, the ingredients were pre-cured in this device. The particles were magnetized and form chains aligned along the magnetic field direction in this progress. Finally, the plate vulcanizing press was used to vulcanize the ingredients.

Rheological or mechanical properties of the MRE cured were characterized by using a parallel-plate rheometer (Physica MCR 301, the Anton Paar). The measurement procedure was similar to that reported by Li et al. (2004). Contrary to conventional testing of MR fluids, the gap h in this study varies so that the sample is under various compression statuses. (The initial gap equals to 1.2 mm.) In other words, these samples are under various squeeze strains. In this study, three typical squeeze strains, 1.3, 2.6, and 3.9%, were selected for the study of field induced shear modulus of MRE samples, as shown in Figure 1. It can been from this figure that shear modulus increases steadily with the increase of magnetic field at a certain squeeze strain. At a constant magnetic field, the modulus shows an increasing trend with the squeeze strain. It is similar to the squeeze-strengthen effect in MR fluids reported (Tang et al., 2000; Li and Zhang, 2008). This effect is promising as it provided another approach for increasing MRE modulus without following the conventional increasing field method. The excitation frequency and amplitude also influence the modulus of MRE. However, when the excitation frequency range is not too large (for example varying from 10 to 100 Hz) and the excitation amplitude is not too big (for example smaller than 0.1%), the influence of excitation frequency and amplitude could be ignored.

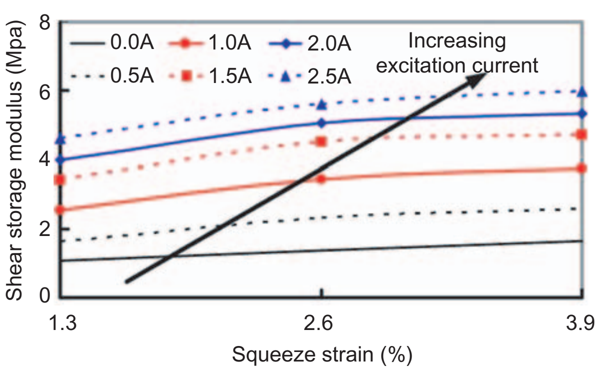

Figure 1. The shear storage modulus of MRE.

To further study this effect, the increment ΔG and relative increment modulus $\Delta G/G_{\varepsilon=2.6\%}$ at different magnetic fields were obtained and shown in Figure 2. Here $\Delta G = G_{\varepsilon=3.9\%} - G_{\varepsilon=1.3\%}$, where $G_{\varepsilon=3.9\%}$, $G_{\varepsilon=2.6\%}$, and $G_{\varepsilon=1.3\%}$ are shear storage modulus at the squeeze strain of 3.9, 2.6, and 1.3%, respectively.

As shown in Figure 2(a), the increment ΔG induced by squeeze strain increases as the excitation current increases; its increasing rate decreases as the excitation current increases. As shown in Figure 2(b), the relative increment modulus $\Delta G/G_{\varepsilon=2.6\%}$ varies from 20% to 40% and decreases as the excitation current increases.

These results demonstrated that the squeeze strain plays a significant role in enhancing the MR effect. Thus, both the magnetic field and the dynamic squeeze strain can work together to effectively control the shear storage modulus of MRE in a dynamic way.

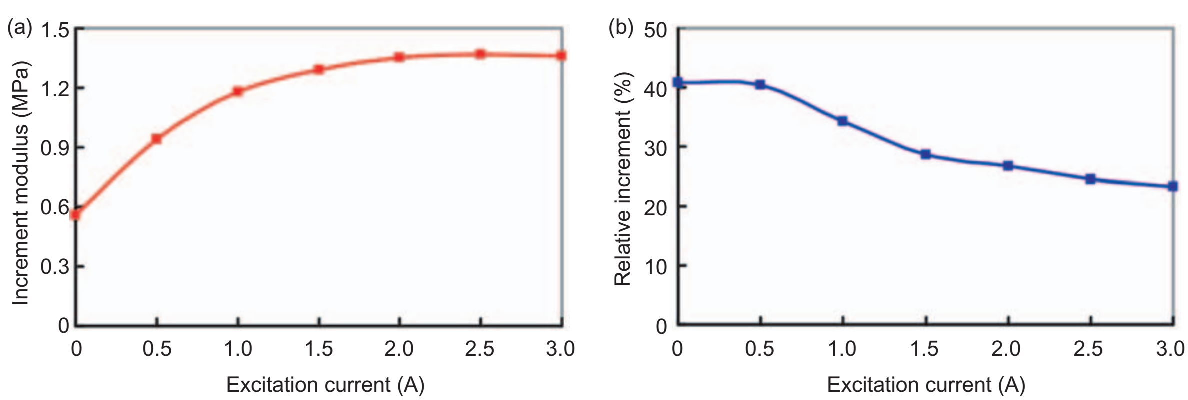

Figure 2. The detail enhanced effect of squeeze strain on shear storage modulus: (a) the increment ΔG; (b) the relative increment modulus $\Delta G/G_{\varepsilon=2.6\%}$.

THE MECHANICAL STRUCTURE AND WORKING PRINCIPLE OF DSTDVA

Mechanical Structure Conceptual Design

As has been shown in the previous section, both the magnetic field and the dynamic squeeze strain can work together to effectively control the shear storage modulus of MRE in a dynamic way. In this study, the excitation winding is used to generate a quasi-static magnetic field while the terrace PZT actuator is applied to control the required MRE squeeze strain in a dynamic way. The schematic of the proposed MRE-PZT DSTDVA is described in Figure 3.

As shown in Figure 3, this device consists of five main parts: a dynamic mass, a static mass, a smart spring element with MRE, controllable DC current source I, and controllable AC voltage source V. The dynamic mass is composed of a C-shape magnetic conductor, excitation winding, moveable arm, and terrace PZT actuator. The base is the only static mass. MREs are stuck between moveable arm and base for connecting both the dynamic mass and the static mass. C-shape magnetic conductor and moveable arm form the closed C-shape magnetic circuit. Excitation winding, controllable DC current source I, and the closed C-shape magnetic circuit apply a controllable quasi-static magnetic field on the MRE. The terrace PZT actuator is thrust through by moveable arm and fixed between C-shape magnetic conductor and moveable arm.

PZTs have been used to remove damping to improve the performance of ATVAs (Kidner and Brennan, 1999). Here, the terrace PZT actuator is designed to apply a dynamic squeeze strain in the direction of particles chain. Its scheme is described in Figure 4.

As shown in Figure 4, d_{33} is used to apply a force on MRE. Its strain is about 0.25%. L_{PZT}/L_e is designed to be larger than 10 and the area of its cross section is nearly the same as the area of MRE. Considering the modulus of PZT is much larger than that of MRE, a dynamic squeeze strain of MRE can approach to the deformation of PZT and be larger than 2%. L_c, L_{PZT}, L_b, and L_e are designed to ensure MRE with 2.6% squeeze strain initially. The minimum of the squeeze strain is controlled to be larger than 1% to ensure a minimum pressure between the MRE and the base and that between MRE and moveable arm is larger than $104\,\mathrm{N/m^2}$.The glue would not be destroyed in this pressure.

Therefore, when the quasi-static magnetic field and dynamic squeeze strain are applied on the MRE at the same time, MRE works in the mode shown in Figure 5.

As shown in Figure 5, this MRE sample works in a shear mode where the magnetic field is perpendicular to the shear direction. The dynamic squeeze strain in the direction of particles chain is applied by the PZTs. Thus, by controlling the magnetic field and the squeeze strain, both the shear storage modulus of MRE

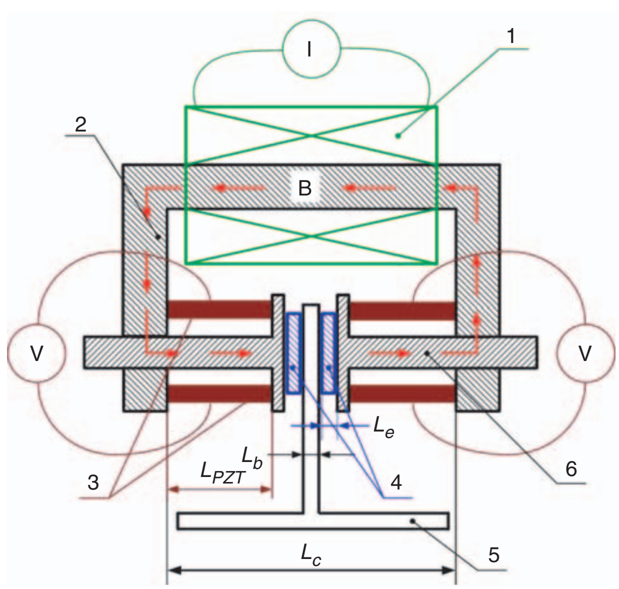

Figure 3. *The scheme of the proposed DSTDVA 1. Excitation winding; 2. C-shape magnetic conductor; 3. Terrace PZT actuator; 4. MRE; 5. Base; 6. Moveable arm.*

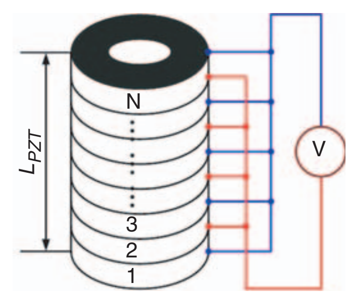

Figure 4. *The scheme of terrace PZT actuator.*

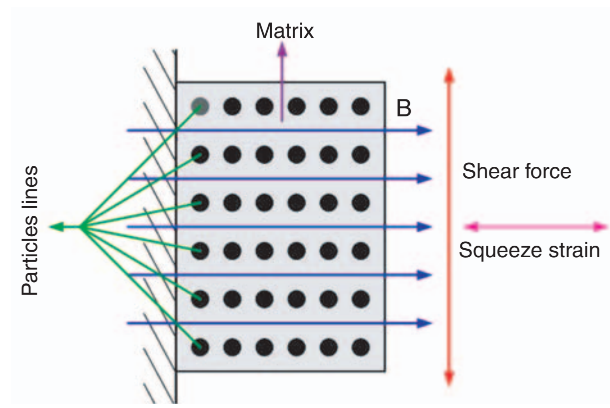

Figure 5. *The directions of magnetic field, shear force, and squeeze strain.*

and the stiffness of the device can be controlled in a dynamic way.

Modeling Analysis

As shown in Figure 3, the stiffness of the proposed absorber $k_a = 2G_eS_e/L_e$, where G_e is the storage modulus of MRE, S_e is the area of single piece MRE, L_e is the thickness of MRE. S_e and L_e are constant for an assembled absorber. When G_e is controlled by the magnetic field and the squeeze strain, the stiffness of the proposed absorber k_a can be changed. The damping also changes at the same time. Therefore, the proposed absorber could be modeled as a single-degree-of-freedom (SDOF) mass-spring-damping system. When the proposed absorber is applied on a SDOF primary system, the whole system is modeled as a SDOF primary system with DVA, as shown in Figure 6.

In this figure, m_p, k_p, and c_p are the mass, stiffness, and damping of the primary system, respectively; m_a, k_a, and c_a are the mass, stiffness, and damping of DVA, respectively. x_a and x_p are the displacement of the dynamic mass and the primary system, respectively. $y_a = x_a - x_p$. f is the excitation force applied on the primary system; $f = F\sin\omega t$, ω is the excitation frequency. The equations of motion can be expressed as

$$(m_p + m_a)\ddot{x}_p + c_p\dot{x}_p + k_px_p + m_a\ddot{y}_a = F\sin\omega t, \qquad (1a)$$

$$m_a(\ddot{x}_p + \ddot{y}_a) + c_a\dot{y}_a + k_ay_a = 0 \qquad (1b)$$

Conventional MRE-based ATVAs adjust their stiffness in a quasi-static way while the proposed MRE-PAT DSTDVA adjust their stiffness in a dynamic way. Figure 7(a) and (b) shows working principles of these two systems. For the conventional MRE ATVAs as shown in Figure 7(a), the controllable stiffness is represented as $k_a = k_{a0} + \Delta k_a$, where Δk_a is actually controlled by the adjustable staticdependent on the magnetic field and equals to $m_a\omega^2 - k_{a0}$. Their nature frequency tracks the excitation frequency and keeps unchanged until the excitation frequency varies (Franchek et al., 1996; Buhr et al., 1997; Hill and Synder, 2002; Rustighi et al., 2005). For our proposed MRE-PZT DSTDVA, the stiffness of which is given by $k_a = k_{a0} + \Delta k_{as} + \Delta\widetilde{k}_{ad}$, where Δk_{as} is also actually controlled by the adjustable static controlled by magnetic field and equals to $m_a\omega^2 - k_{a0}$; $\Delta\widetilde{k}_{ad}$ is controlled in a dynamic way by properly squeezing strain, which is able to overcome the decay effect of damping on the vibration absorption capacity.

As shown in Figure 7(a), when Δk_a is set to $m_a\omega^2 - k_{a0}$, the conventional MRE ATVAs apply the spring force F_k in the opposite direction of $\dot{x}_p$. The damping force F_c is applied on the primary system simultaneously. The phase difference between F_k and F_c is 90°. F_k suppresses the vibration of the primary system while F_c limits the vibration suppressing effect.

Comparing the proposed MRE-PZT DSTDVA with conventional MRE ATVA, the only difference between the two kinds of absorbers is that an additional force $F_{kd} = \Delta k_{ad}y_a$ is introduced to decrease the decay effect of damping on the vibration absorption capacity, as shown in Figure 7(b). Its working mechanics is similar to the absorber proposed by Sun et al. (2006). The absorber proposed by Sun introduces active force acting between the absorber and primary system. When the active force equals to the damping force applied on absorber, the damping force is canceled and the vibration of the primary system can be reduced to zero. Similarly, the proposed DSTDVA based on MRE also applies active force F_{kd} between absorber and primary system. Its characteristic is that active force F_{kd} is applied by Δk_{ad} based on the enhanced effect. If $F_{kd} = -c_a\dot{y}_a$, the damping force of the proposed absorber is completely canceled and the vibration of the primary system is completely suppressed.

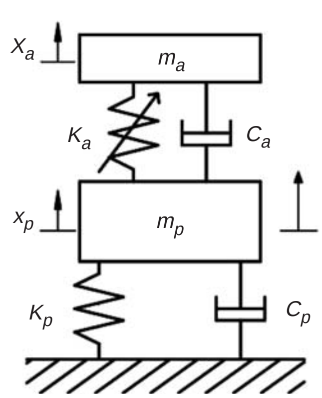

Figure 6. The scheme of the primary system with DVA.

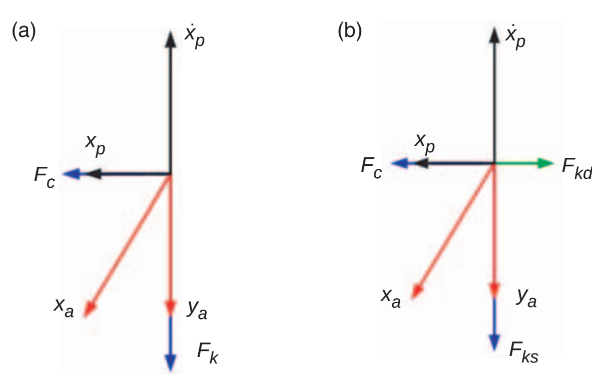

Figure 7. The relationship between movement and force: (a) the usual ATVAs based on MRE; (b) the proposed DSTDVA based on MRE.

Harmonic analysis is employed to minimize the first harmonic vibration of the primary system. The details are as follows.

Let

$$x_p = a_0 + a_1 \cos\omega t + b_1 \sin\omega t + a_2 \cos 2\omega t + b_2 \sin 2\omega t + a_3 \cos 3\omega t + b_3 \sin 3\omega t, \quad (2a)$$

$$y_a = c_0 + c_1 \cos\omega t + d_1 \sin\omega t + c_2 \cos 2\omega t + d_2 \sin 2\omega t + c_3 \cos 3\omega t + d_3 \sin 3\omega t, \quad (2b)$$

$$\Delta\widetilde{k}_{ad} = \Delta k_{ad} \sin(2\omega t + \varphi), \quad (2c)$$

then

$$\left(k_p - (m_p + m_a)\omega^2\right)a_1 + c_p\omega b_1 - m_a\omega^2 c_1 = 0, \quad (3a)$$

$$\left(k_p - (m_p + m_a)\omega^2\right)b_1 - c_p\omega a_1 - m_a\omega^2 d_1 = F, \quad (3b)$$

$$-m_a\omega^2 a_1 + c_a\omega d_1 + \frac{1}{2}\Delta k_{ad}(\sin\varphi(c_1 + c_3) + \cos\varphi(d_3 + d_1)) = 0, \quad (3c)$$

$$-m_a\omega^2 b_1 + c_a\omega c_1 + \frac{1}{2}\Delta k_{ad}(\cos\varphi(c_1 - c_3) - \sin\varphi(d_1 - d_3)) = 0. \quad (3d)$$

In order to suppress the first harmonic vibration of the primary system completely,

$$a_1 = b_1 = c_1 = 0, \quad d_1 = -F/m_a\omega^2, \quad 0.5\Delta k_{ad}\cos\varphi + c_a\omega = 0. \quad (4)$$

As shown in Equation (4), the first harmonic vibration of the primary system can be suppressed completely. The control law is

$$\Delta k_{as} = m_a\omega^2 - k_{a0}, \quad \Delta\widetilde{k}_{ad} = \Delta k_{ad}\sin(2\omega t + \varphi), \quad 0.5\Delta k_{ad}\cos\varphi + c_a\omega = 0. \quad (5a-c)$$

As shown in Equation (5c), when $\varphi = \pi$, Δk_{ad} has the minimum value and $\Delta k_{ad\_\min} = 2c_a\omega$.

STUDY OF THE VIBRATION SUPPRESSION CAPACITY OF THE PROPOSED DSTDVA

The Control Strategy and the Control System

Figure 8 depicts the control system of the proposed DSTDVA based on MRE. The control system composes of three main parts: the DC current source controller, the AC voltage source controller, and the combined controller. The control strategy is a kind of combined strategy (the tuning strategy and the ON–OFF strategy). The tuning strategy is used in the DC current source controller. The ON–OFF strategy is used in the AC voltage source controller. The combined control strategy is designed. The tuning strategy used is similar to the one proposed by Kidner and Brennan (2001) and Wu and Shao (2007). They proposed to adjust the stiffness of the absorbers to force the absorber and the primary system in quadrature. Here, the tuning strategy is used to adjust the stiffness of the proposed DSTDVA to force the relative movement of the absorber and the movement of the primary system in orthogonal. The stiffness is adjusted by the quasi-static magnetic field induced by

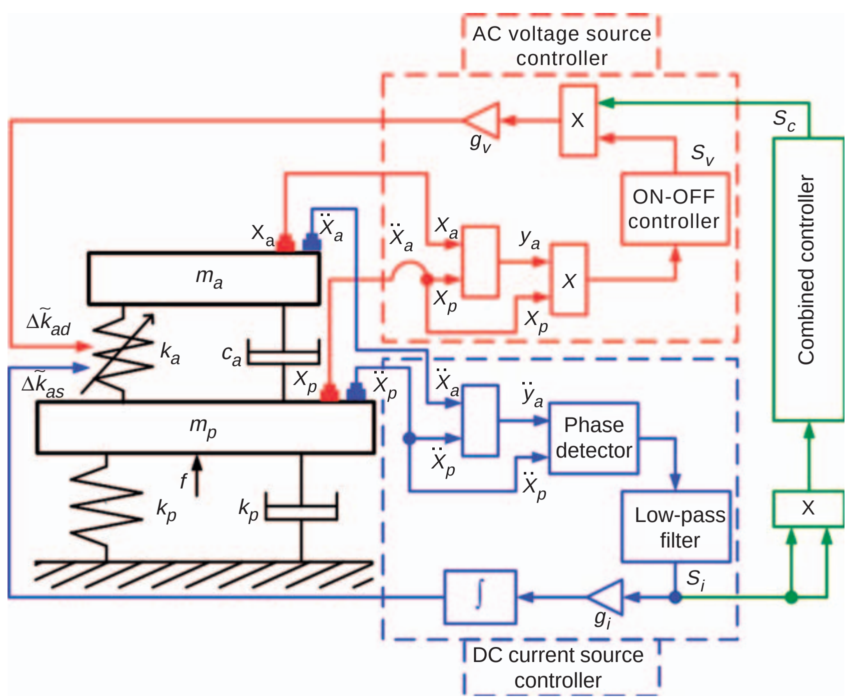

Figure 8. The control system of the proposed DSTDVA based on MRE.

the controllable DC current source I. The ON–OFF strategy is based on viscous damping. The combined controller is designed to determine whether terrace PZT actuators work.

The control strategy is as follows:

$$
\begin{aligned}
&\Delta\dot{k}_{as} = g_i S_i, \quad S_i = G_i(\ddot{y}_a, \ddot{x}_p) = \frac{1}{AT}\int_0^T \ddot{y}_a \ddot{x}_p \, \mathrm{d}t, \\
&A = \frac{|\ddot{y}_a||\ddot{x}_p|}{2}, \quad \ddot{y}_a = \ddot{x}_a - \ddot{x}_p, \quad \Delta\tilde{k}_{ad} = g_v S_v S_c, \\
&S_v = G_v(y_a, x_p) = \begin{cases} 1 & y_a x_p \le 0 \\ -1 & y_a x_p < 0 \end{cases}, \\
&y_a = x_a - x_p, \quad S_c = G_c(S_i) = \begin{cases} 1 & S_i^2 \le B \\ 0 & S_i^2 > B \end{cases}, \qquad (6a-h)
\end{aligned}
$$

where $\ddot{x}_a$ and $\ddot{x}_p$ are the absolute accelerations of the absorber and the primary system; x_a and x_p are the absolute displacements of the absorber and the primary system; $\ddot{y}_a$ and y_a are the relative acceleration and the relative displacement of the absorber; Δk_{as} is the stiffness increment induced by the excitation current of the controllable DC current source I based on MR effect; $\Delta\tilde{k}_{ad}$ is the stiffness increment induced by the voltage of the controllable AC voltage source V based on the enhanced effect of squeeze strain on shear storage modulus shown in 'The Enhanced Effect of Squeeze Strain on shear Storage Modulus' section; S_i is the normalized time-averaged product of the relative acceleration $\ddot{y}_a$ of the absorber and the absolute acceleration $\ddot{x}_p$ of the primary system; A is the normalized factor; its function works by using the phase detector and the low-pass filter (Wu and Shao, 2007). S_v is the output of the ON–OFF controller; g_i is the feedback factor of $\Delta\dot{k}_{as}$; g_v is the feedback factor of $\Delta\dot{k}_{ad}$; S_c is the output of the combined controller; if $S_i^2 < B$, the terrace PZT actuators work; if $S_i^2 > B$, the terrace PZT actuators don't work.

Vibration Absorption Capacity

The vibration absorption capacity is evaluated by simulation study. The initial squeeze strain of MRE is set to 2.6%. The terrace PZT actuators are designed to control the squeeze strain varying from 1.3 to 3.9%. As shown in Figure 2(b), the relative increment modulus $\Delta G/G_{\varepsilon=2.6\%}$ varies from 20% to 40%. Therefore, the amplitude of $\Delta\tilde{k}_{ad}$ versus the current stiffness $k_{a0} + \Delta k_{as}$ varies from 10% to 20%. Define $\alpha = |\Delta\tilde{k}_{ad}|/(k_{a0} + \Delta k_{as})$. The simulation parameters are selected as follows: $m_p = 400\,\mathrm{kg}$, $k_p = 2.668 \times 10^6$ N/m and $c_p = 3267\,\mathrm{N/(m/s)}$; $m_a = 5\,\mathrm{kg}$, $k_{a0} = 8340\,\mathrm{N/m}$ and $c_a = 41\,\mathrm{N/(m/s)}$; $f = 7\sin\omega t(N)$, $\alpha = 0.2$, $B = 0.05$. The proposed MRE-PZT DSTDVA is initially fixed on the primary system at point A and starts to control its stiffness at point B. The results are described in Figure 9.

As shown in Figure 9, in the period between point A and B, the stiffness of the absorber does not change and the absorber work as a passive absorber. It suppresses the vibration of the primary system just a little. At point B, the proposed MRE-PZT DSTDVA starts to

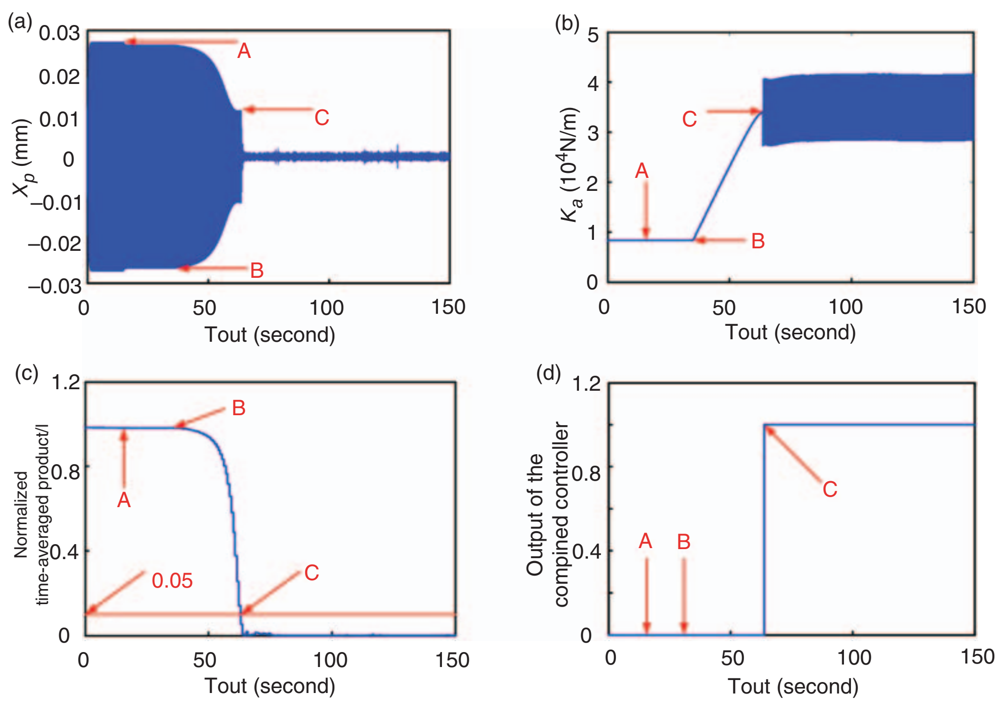

Figure 9. *The simulation results of the proposed MRE-PZT DSTDVA with $\alpha = 0.2$, $B = 0.05$: (a) the displacement of the primary system; (b) the stiffness of DSTDVA; (c) the normalized time-averaged product; (d) the output of the combined controller.*

control its stiffness. In the period between point B and C, the normalized time-averaged product is larger than 0.05. The output of the combined controller equals to 0. The terrace PZT actuator does not work and its stiffness is tuned in a quasi-static way. It greatly suppresses the vibration of the primary system. After point C, the normalized time-averaged product is smaller than 0.05 and the output of the combined controller equals to 1. Therefore, the terrace PZT actuator starts to work and its stiffness is tuned in a dynamic way. It further suppresses the vibration of the primary system.

The results of those conventional MRE-based quasi-static tuned ATVAs are described in Figure 10. The conventional MRE-based quasi-static tuned ATVA is initially fixed on the primary system at point A and its stiffness does not change before point B. It suppresses the vibration of the primary system just a little. At point B, the conventional MRE-based quasi-static tuned ATVA starts to control its stiffness. As its stiffness approaches the target value $m_a\omega^2 = 3.336 \times 10^4$, the vibration of the primary system is suppressed gradually.

Comparing Figure 9 and 10, before point C, the stiffness of the two absorbers are the same and they suppress the vibration of the primary system equally. After point C, the stiffness of the proposed MRE-PZT DSTDVA is controlled in a dynamic way while the stiffness of the conventional MRE-based quasi-static tuned ATVA is controlled in a quasi-static way. The vibration of the primary system with the proposed MRE-PZT-DSTDVA is much smaller that that of the conventional MRE-based quasi-static tuned ATVA. That is to say, the proposed MRE-PZT-based DSTDVA exhibited more effective suppression capabilities than those conventional MRE-based quasi-static tuned vibration absorbers.

Based on the test results of the MRE used, α varies from 10% to 20%. α indicates the enhanced effect of the squeeze strain on shear storage modulus and greatly influences the vibration suppression capabilities. Its effect is shown by comparing Figure 9 ($\alpha = 0.2$) and Figure 11 ($\alpha = 0.1$). As shown in Figure 9 and 11, before point C, the stiffness of the two absorbers is the same and they suppress the vibration of the primary system equally. After point C, the amplitude of the proposed MRE-PZT DSTDVA with $\alpha = 0.2$ is much larger than that with $\alpha = 0.1$. The vibration of the primary system with $\alpha = 0.2$ is much smaller that that with $\alpha = 0.1$. That is to say, α greatly influences the vibration suppression capabilities; the larger α is, the more effective vibration suppression capabilities it has.

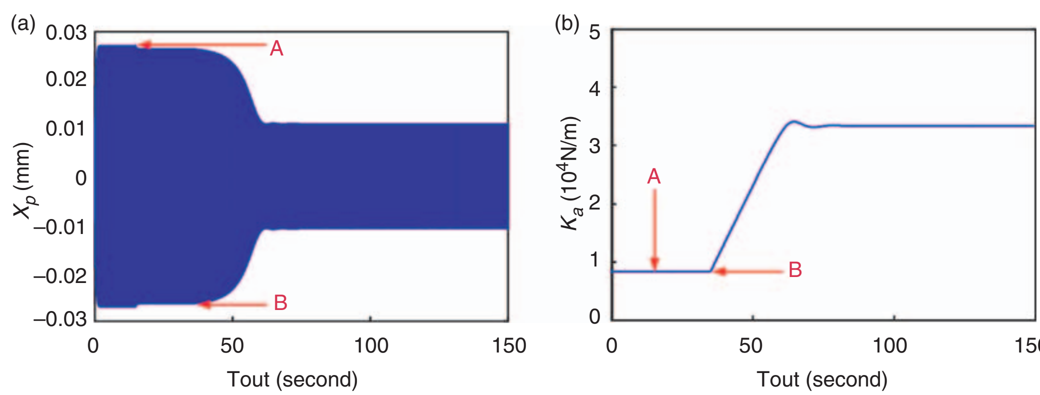

Figure 10. *The simulation results of the conventional MRE-based quasi-static tuned ATVA: (a) the displacement of primary system; (b) the stiffness of ATVA.*

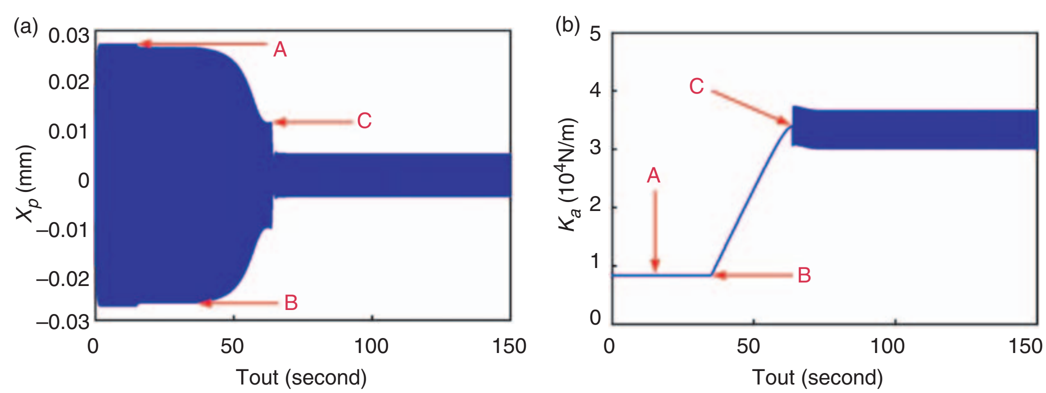

Figure 11. *The simulation results of the proposed MRE-PZT DSTDVA with $\alpha = 0.1$, B = 0.05: (a) the displacement of primary system; (b) the stiffness of DSTDVA.*

CONCLUSIONS

In this article, a new design concept: DSTDVA based on MRE, is proposed. This DSTDVA based on MRE is based on the MR effect and the enhanced effect of squeeze strain in the direction of particles chain on shear storage modulus. The harmonic analysis is used to minimize the first harmonic vibration of the primary system theoretically.

The vibration suppression capacity is further evaluated by the simulation results. Its control system and combined control strategy are proposed. The control system composes of three main parts: the DC current source controller, the AC voltage source controller and the combined controller. The tuning strategy is used in the DC current source controller. The ON–OFF strategy is used in the AC voltage source controller. The combined control strategy is designed. The simulation results indicated that the proposed MRE-PZT-based DSTDVA exhibited more effective suppression capabilities than those conventional MRE-based quasi-static tuned vibration absorbers; the stronger the enhanced effect of squeeze strain on MRE's shear storage modulus is, the more effective vibration suppression capabilities the proposed MRE-PZT-based DSTDVA has.

ACKNOWLEDGMENTS

Financial support from NSFC (Grant No. 10672154) and SRFDP of China (Project No. 20050358010) is gratefully acknowledged.

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