Magnetorheological elastomer and its application on impact buffer

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Abstract. In this study, a new magnetorheological elastomer (MRE) based buffer is proposed and its vibration isolation performance is investigated. The MRE buffer with a compact structure is first designed in order to accomplish the maximization of the variable stiffness range. The working characteristics of the MRE buffer are then measured and the model of MRE is established. On the basis of the experimental data, the control model of the MRE buffer is also formulated. A two-degree-of-freedom dynamic model with an MRE buffer is then developed. An intelligent control strategy, human simulated intelligent control (HSIC), is proposed to reduce the impact during the drop crash. Finally, the proposed MRE buffer and controller are validated numerically and experimentally. The results show that the proposed MRE buffer and the control strategy can reduce the impact acceleration effectively.

1. Introduction
Magnetorheological (MR) materials include magnetorheological fluid (MRF), MR foams and MRE, whose rheological properties can be controlled by the application of an external magnetic field[1]. The most common MR material is MRF. There are magnetically polarizable particles suspended in the viscous fluid. In recent years, the MRF technology has made significant advancements [2] and many applications such as the automotive suspension vibration control [3], the earthquake resistance [4], clutch [5] etc. However, MRFs are prone to particle settling with time due to the density mismatch of magnetic particles and the carrier fluid, which may degrade the MR effect. Therefore, another smart material, MRE, has received much attention in recent years.

As solid analogy of MRF, MRE, which includes a wide variety of composite materials, typically consists of magnetically polarizable particles dispersed in a polymer medium with many advantages. Compared to MRF, MRE can avoid some disadvantages such as settling of particles normally associated with MRF. MRE does not require channels or seals to hold or prevent leakage and thus can avoid the particle sedimentation associated with MRF. In addition, the valuable characteristic of MRE is that its mechanical properties such as the storage and loss modulus can be tuned reversibly by the application of an external magnetic field. The field dependence of the mechanical properties enables
the construction of controllable elastomeric components. As a result, MRE possesses many potential
engineering applications for vibration control in damping and vibration isolation systems such as
engine mounts and suspension bushings to reduce noise and vibration.

Due to the little adjustment range of variable stiffness, there are only few application reports about
MRE when comparing to the MRF. The salient feature of adjustable stiffness has been studied in
vibration isolation. Several researches have shown the shift of resonant frequency can be achieved by
the MRE buffer. For example, the tunable automotive mounts and bushings based on MRE were
developed by Ginder et al. [6]. They found that the suspension resonances excited by torque variation
could be suppressed by shifting the resonance away from the excitation frequency. Another similar
adaptive tuned vibration buffer based on MRE was studied by Deng et al. [7]. Their results show that
the natural frequency of the buffer based on MRE can be tuned from 55 to 82 Hz. In their later another
work [8], the shift-frequency capability of the adaptive buffer was theoretically and experimentally
evaluated. The results demonstrate that the natural frequency of the proposed buffer can be tuned from
27.5 Hz to 40 Hz. Collette et al. [9] investigated numerically two systems based on MRE according to
the measured characteristics from published studies. The numerical results show that the command
ability of the elastomer improves the isolation performance of the MRE isolator under a frequency
varying harmonic excitation, and decreases the stress level of the MRE dynamic vibration buffer under
a random excitation. Liao et al. [10] attached a voice coil motor to a conventional MRE buffer to
improve its performance. The results indicate that the resonant frequency of the proposed buffer could
be tuned from 11 to 18 Hz whereas the damping ratio would reduce from 0.19 to 0.005. Besides the
shift resonant frequency, Opie et al. [11] studied a magnetically biased MRE-based vibration isolator
in the primary isolation system. The experimental results show that the MRE isolator and the semi-
active controller system can reduce resonances and payload velocities by 16-30% when compared to
passive systems. To improve the isolation performance of the traditional floating raft system, Sun et al.
[12] proposed a buffer based on MRE. The results show that the adaptive buffer can improve the
isolation performance of floating raft system in a wide frequency range. These researches have shown
that tunable vibration buffers based on MRE can achieve better isolation performance than traditional
vibration buffers. However, the research focus on steady vibration system and is still in early stage for
MRE, most of the study focused on preparation, mechanical tests and simple physical modelling of
MRE, and little work has been done in some transient impact isolation systems and control.

Consequently, the main contribution of this study is to propose a new adaptive variable stiffness
buffer based on MRE and evaluate its vibration control performance in transient impact isolation
systems. To accomplish it, a new vibration buffer based on the fabricated MRE is developed and its
control model is formulated on the basis of measured working characteristics. Then a two-degree-of-
freedom dynamic model with the proposed MRE buffer is constructed and a human simulated
intelligent controller is yet formulated. Numerical and actual drop test are performed to validate the
proposed MRE buffer and the proposed control strategy.

2. Development of MRE buffer

2.1. Structure design of MRE
In this study, an adaptive variable stiffness buffer based on MRE is designed and manufactured to
realize variable stiffness characteristics of the buffer, which is schematically shown in Figure 1. The
buffer consists of a coil, two smart MREs, the outer cylinder and the piston. Two MREs are clung to
both the outer cylinder and the piston, respectively. The magnetic field is generated by the coils and
can be tuned by tuning the coil current. By the motion of piston, the shear deformation of MRE will
appear. The magnetic field exits in the MRE which is perpendicular to the motion of the piston after
the current is applied to the coil. The shear modulus of the MRE is altered when subjected to an
external magnetic field. Thus, the elastic force of the buffer is controlled by the intensity of the
magnetic field.
In absence of magnetic field, the buffer will produce an elastic force only caused by the MRE’s passive shear resistance. If a certain level of magnetic field is supplied to the buffer, the MRE buffer produces an additional and variable elastic force owing to the increased shear modulus of the MRE. The elastic force of the MRE buffer can be continuously tuned by controlling the intensity of the magnetic field.

2.2. Model of MRE
To simplify the analysis of the MRE buffer, a Kelvin-Voigt model is adopted in this study. The model consists of a constant stiffness spring, a variable stiffness spring and a damper with constant damping coefficient in parallel. In the shear direction, \( k \) is given by [7]

\[
 k = \frac{G A}{h} = \frac{(G_0 + \Delta G) A}{h} = \frac{G_0 A}{h} + \frac{A}{h} \frac{40\phi\mu_1\mu_0^2 H_0^2}{h} \left(\frac{R}{d}\right)^3 \zeta = k_e + k_{MRE}
\]

where \( G \) denotes the shear modulus of MRE and consists of two terms, an initial shear modulus \( G_0 \) without a magnetic field and a shear modulus increment \( \Delta G \) with applying a magnetic field; \( A \) is the shear area, and \( h \) is the thickness of MRE; \( \mu_1 \) and \( \mu_0 \) are the relative permeability for the particles and silicon rubber matrix, respectively; \( \phi \) is volume fraction; \( R \) is the average particle radius; \( d \) is the particle distance before deflection; \( H_0 \) is the applied magnetic field intensity; \( \beta \approx 1; \zeta \approx 1.202 \); \( k_e \) is the equivalent stiffness coefficient and \( k_{MRE} \) is the controllable stiffness part of the MRE.

For simplification, the \( F_{MRE} \) can be approximately described as a quadratic function of the input current

\[
 F_{MRE} = dI^2 + eI + f
\]

where \( d, e, f \) are constants and obtained by fitting the measured experimental data, \( I \) is the controlled current supplied to the coil of MRE buffer.

2.3. Working features test of MRE
To measure working features of the MRE buffer, an experimental platform has been set up, which is shown in Figure 2 and 3. The test system include the MRE buffer, the force sensors, electromagnetic vibration table and data acquisition instrument. A vibrator produced by B&K Co. is used to drive the MRE buffer, and the displacement and force are measured. The velocities are calculated using a central differences approximation. Sinusoidal command signals are used.

In this study, the excitation frequencies include 25, 50 and 75 Hz and the displacement amplitudes have the same value of 0.5mm. Five kinds of constant currents are applied to the MRE buffer to observe the characteristics of the buffer. The applied input current is from 0 to 2 A with the increment of 0.5 A. For brevity, only the force-displacement hysteresis under the excitation frequency of 25 Hz is given in Figure 4. The equivalent stiffness of the MRE buffer is calculated and shown in Figure 5.
(1) From the Figures 4-5, it can be seen that the elastic force will increase with the increase of the input current.
(2) It is well known the damping properties can be controlled by the application of magnetic field. However, because the enclosed area of the force-displacement is almost invariable in this study, it is considered the damping characteristic is invariable.
(3) It is noticed that the stiffness is not symmetric with respect to the displacement zero. The tests are repeated for several times. The same phenomenon still existed. The reason is the modulus is different for the case of compression and tension.
(4) In addition, on the basis of the test device in Figure 3, the time response of the MRE buffer under the triangular wave signal excitation is measured, and the excitation is the force. The measured results are shown in Figure 6. When the control current is applied during the back half period of the triangular wave, the force response is different from the shape of the excited signal. There is a time delay, which is about 7 ms. Therefore, it can be found that the response time of MRE buffer is about 7 ms, which is fast enough to formulate the later control strategy.
3. Dynamic model of MRE buffer system

MRE buffer system is a multi-degree-of-freedom complex vibration system. In order to research vibration performance and design of control law conveniently, it is necessary to simplify the MRE buffer system. Thus the following assumptions are given:

(1) MRE has the advantage of compact structure and light weight. In the work process, the shock of sample is larger than the one in normal operations. Therefore, in the force analysis of spring mass and unspring mass, the influence of gravity force should be ignored.

(2) By the properties of MRE, the shear modulus caused by magnetic field will increase with the exciting current. However, the loss factors have no significant change, and thus the equivalent damping coefficient of MRE may be regarded as constant.

(3) In work process, the shock suffered is mostly vertical without consideration of pitch vibration and tilt angle vibration of MRE.

Based on the above analysis and the designed MRE buffer structure in Figure 1, a two-degree-of-freedom impact dynamic model, which consists of a constant stiffness spring, a variable stiffness spring and a damper with constant damping coefficient in parallel, is constructed to check the performance of the MRE buffer in Figure 7.

According to the Newton’s second law, the dynamic model can be derived as

\[ M_s \ddot{y}_1 + (C_s + C_e)(\dot{y}_1 - \dot{y}_2) + K_e(y_1 - y_2) + F_{MRE} = 0 \]  \hspace{1cm} (3)

\[ M_u \ddot{y}_2 - (C_s + C_e)(\dot{y}_1 - \dot{y}_2) - K_s(y_1 - y_2) + K_u(y_2 - w) - F_{MRE} = 0 \]  \hspace{1cm} (4)

Where \( M_s \) and \( M_u \) are the sprung mass the unsprung mass, respectively. \( C_s \) is the damping constant of an air damper. \( C_e \) is the equivalent damping constant of the MRE buffer. \( K_s \) and \( K_e \) are the fixed stiffness coefficient and the controllable stiffness force, respectively. \( y_1, y_2, w \) are displace of substrate, displace of sprung mass and displace of unsprung mass, respectively. \( \dot{y}_1, \dot{y}_2 \) are the derivatives of \( y_1, y_2 \), respectively, and \( \ddot{y}_1, \ddot{y}_2 \) are the second derivatives of \( y_1, y_2 \), respectively.

4. Human simulated intelligent controller development

In order to adjust the variable stiffness of the MRE buffer, an intelligent control algorithm, human simulated intelligent control (HSIC), is proposed, which has been applied successfully in the vibration control of the vehicle MR suspension in our prior works [13-15]. The original human simulated intelligent control (HSIC) algorithm, which was firstly proposed by Zhou et al. in 1983 [16], has become a fundamental and systematic method used in resolving some general industrial control
problems for the last twenties years. In recent years, the HSIC theory has been further advanced through combing with the schema theory of modern cognitive science in recent years. After having studied for many years [17], HSIC theory based on SMIS has come into being. The theory provides a more effective and systematic method in resolving some complex control problems.

According to the general design methodology of HSIC theory, the sensed schema, the motion schema and the association schema are formulated in the following.

4.1. Sensed schema

The sensed schema can be described by

\[ S_P = < R, Q, K, \otimes, \Phi > \]  \hspace{1cm} (5)

in which \( R, Q, K, \otimes \) and \( \Phi \) are the input information set, the characteristic primitive set, the relation matrix, the operational symbol and the characteristic model set, respectively. The characteristic primitive set is selected according to the states of MRE buffer can be selected as

\[ Q = [q_1, q_2, q_3, q_4, q_5]^T \]  \hspace{1cm} (6)

where \( q_1 \Rightarrow a \ddot{a} \geq 0 \), \( q_2 \Rightarrow a \ddot{a} < 0 \), \( q_3 \Rightarrow a > a_{set} \), \( q_4 \Rightarrow a \leq a_{set} \), \( q_5 \Rightarrow a > 0 \), \( a \) is the impact acceleration value, \( a_{set} \) is the threshold value of acceleration. The relation matrix is set as

\[ K = \begin{bmatrix} 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 1 \end{bmatrix} \]  \hspace{1cm} (7)

As a result, the sensed modal can be written as,

\[ \Phi = K \otimes Q = \begin{cases} \phi_1 & |a \ddot{a} \geq 0, a \leq a_{set}, a > 0, \\ \phi_2 & |a > a_{set}, \\ \phi_3 & |a \ddot{a} < 0, a \leq a_{set}, a > 0 \end{cases} \]  \hspace{1cm} (8)

4.2. Motion schema

The motion schema can be described as

\[ S_M = (R, P, L, \Psi, U) \]  \hspace{1cm} (9)

in which, \( R \in \Sigma^d \), \( P = [p_1, p_2, \cdots, p_{\nu}, \cdots, p_n]^T \in \Sigma^n \), \( p_i = f(R) \), \( L \in \Sigma^{\nu \times \nu} \), \( \Psi = \{ \psi_1, \psi_2, \cdots, \psi_{\nu}, \psi_{\nu} \} \in \Sigma^\nu \), \( \psi_i = L \cdot P = \sum_{j=1}^{\nu} \psi_j \), \( U = L \cdot P \) are the input information set, the
control mode primitive set, the coordination relation matrix, the control mode set and the control output, respectively.

In this study, the control modal includes three situations:

1. The first control modal is selected as proportional control during the first phase when the acceleration of sprung mass is below the threshold value.

\[
p_1 = f_e k_p a
\]

where \( k_p \) is the proportional gain and \( f_e \) is the adjusting factor.

2. Once the acceleration is bigger than the threshold value and the second control modal of bang-bang control is activated,

\[
p_2 = -f'_e k_m
\]

where \( f'_e \) is also an adjusting factor, \( k_m \) is the maximum value of \( k_p \).

3. The third control modal is the proportional control during the acceleration of sprung mass is smaller than the threshold value and can be written as

\[
p_3 = -f'_e k'_p a
\]

In which, \( k'_p \) is the proportional gain.

The modal selection matrix is

\[
L = \begin{bmatrix} 1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1 \end{bmatrix}
\]

and the control modal set is written as

\[
\Psi = \{p_1, p_2, p_3\} = \{\psi_1, \psi_2, \psi_3\}
\]

4.3. Association schema

\[
S_a = \{\Omega : \Phi \rightarrow \Psi\}, \Omega = \{w_1, w_2, w_3\}
\]

where \( W_j \) represents the reasoning procedure of if \( \phi_j \) then \( \psi_j \) (\( j = 1,2,3 \)).

In order to illustrate the HISC idea in the paper, Figure 8 is used to approximate acceleration response of MRE buffer under impact. In section I, states of MRE buffer are satisfied \( \phi_3 \) in sensed schema, so the control strategy is chosen as \( p_3 \) in motion schema. Similarly, in section II (III), states of MRE buffer is satisfied \( \phi_2 \) (\( \phi_1 \)) in sensed schema and control strategy is chosen as \( p_2 \) (\( p_1 \)) in motion schema.

5. Numerical simulation

Before performing the drop test, the numerical simulation is undertaken. The dynamic model of equations (3)-(4) and HSIC controller are developed on the MATLAB/SIMULINK 7.1. In this study, the model parameters are shown in Table 1. These parameters are coming from the direct measurement of actual drop test system.
Table 1. The model parameters.

| Symbols | Unit       | Values    |
|---------|------------|-----------|
| $M_s$   | kg         | 2.85      |
| $M_u$   | kg         | 0.25      |
| $C_s$   | $N/\text{ms}^{-1}$ | 2000  |
| $C_e$   | $N/\text{ms}^{-1}$ | 200    |
| $K_s$   | $N/m$     | 41320     |
| $K_u$   | $N/m$     | $1.0 \times 10^6$ |

Figure 8. Acceleration response of MRE buffer under impact.

To check the control performance, the dynamic system is dropped numerically from a height of 10 cm. The results are shown in the Figures 9-10. From these two figures, it can be found that the maximum impact acceleration of sprung mass of system with control can effectively reduced compared to that without control. However, a slightly longer response time and a bigger displacement are required for the control case. The control output is shown in Figure 11.
6. Drop test and result

To further validate the proposed MRE buffer, a drop test is carried out, which is shown in Figure 12. The spring mass and unsprung mass are connected by the MRE buffer. During the test, the absorbing system is sliding along a guide way vertically. The impact force between the unsprung mass and ground is measured by a force sensor. The acceleration of sprung mass is acquired by the acceleration sensor. In addition, the displacement of sprung mass is also measured by a laser displacement sensor. As comparison, the response of the absorbing system without control is also measured. The height of drop test is 10cm for each test, which is similar to the simulation.
(1) Figures 13 and 14 give the comparison of acceleration and displacement for sprung mass under on-control and off-control, respectively. According to the Figure 13, it can be seen that the maximum acceleration peak of sprung mass under control can be reduced by $12.1 \, \text{m/s}^2$ compared to that of the off-control.

(2) Compared to the simulation, the control performance is limited. There are some reasons for this. For example, the time delay or response time of the MRE buffer is not considered and the control range is still very small. On the other hand, some similar phenomena can also be observed in the actual test, a longer adjusting time is required for both the numerical and actual tests.

(3) From Figure 14, we can find that the MRE buffer under HSIC can not reduce the displacement response of sprung mass and requires much longer adjusting time, which are similar to that of the simulation. In addition, the amplitude of actual test data is larger than that of simulation. The reason may be that the static friction in absorbing system may be neglected in the simulation.

7. Conclusions
In this study, a variable stiffness buffer based on MRE was developed and its vibration buffer capability, which is described by the relations of force and displacement, stiffness and displacement, was evaluated. The measured results shows time respond is fast enough to formulate the control strategy. Meanwhile, the relation between force and current was approximately described as a quadratic function. A two-degree-of-freedom impact dynamic model is developed to describe the accurate MRE buffer dynamic characteristic. The segment controllers under HSIC strategy realized the impact suppression effectively. Through numerical and actual drop test, it showed that the proposed MRE buffer and controller can reduce the maximum impact acceleration comparing to the off-control case.

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