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Isolation and damping properties of magnetorheologic elastomers

C Collette[1], G Kroll[1], G Saive[2], V Guillemier[3], M Avraam[1] and A Preumont[1]

[1] *University of Brussels, 50 av. F.D. Roosevelt, 1050 Brussels, BELGIUM*
[2] *Techspace Aero (SAFRAN Group), 121, route de Liers, 4041 Herstal, BELGIUM*
[3] *MATIS Benelux, 121, route de Liers, 4041 Herstal, BELGIUM*

E-mail: christophe.collette@ulb.ac.be

Abstract. This paper considers two systems based on a magnetorheological elastomer (MRE): a MRE isolator under a frequency varying harmonic excitation and a MRE Dynamic Vibration Absorber (DVA) mounted on a frequency-varying structure under a random excitation. It is shown that the commandability of the elastomer improves the isolation performances in the first case, and decreases the stress level in the structure in the second case.

1. Introduction

Consider a structure fixed on a support through a set of mounts. Often, the mechanical properties of a structure are evolving in time (e.g. changes in mass, temperature, load cycle). If the stiffness and the damping properties of the mounts remain constant, their isolation performances is not always optimal. A technique whose spring constant and damping factor can be changed represents a potentially considerable improvement of the vibration. Along with piezoelectric ceramics and shape memory alloys, the magnetorheological elastomers (MRE) have those capabilities [1, 2].

Measured characteristics from published studies [3] are used to evaluate their isolation and damping performances in two cases. The first is a tunable isolator supporting a structure and subjected to a narrow band excitation. The problem is addressed in section 3, with a single degree of freedom (d.o.f.) MRE isolator. The second is a tunable DVA mounted on a structure whose mass is varying, and that is subjected to a broad band random excitation. The problem is addressed in section 4, with a MRE DVA appended on a flexible structure. In the numerical example, a n-storey like structure has been considered for its simplicity. However, the procedure is applicable to any type of flexible structure. Different kinds of Adaptive DVAs have also been developed ([4, 5] & [6, 7]), but the effect of the MRE DVA on the stress reduction in the structure has not yet been fully addressed. Next section presents the theoretical model of a magnetorheological elastomer, along with its potential applications.

2. Model of a magnetorheological elastomer

Using a simple Kelvin-Voigt model (spring and damper in parallel), the MRE can be characterized by a constant stiffness k and damping coefficient ξ. Experiments [3] have shown

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that, until a saturation value of the applied magnetic field B_s, the values of k and c increase linearly according to

$$k(B) = a_k + b_k B \quad ; \quad \xi(B) = a_\xi + b_\xi B \tag{1}$$

where B is the magnetic field and a_k, b_k, a_ξ, b_ξ are constant quantities. Note that only the shear mode is considered in this paper, as experimental studies have shown that, in this direction, the relative increase in stiffness is the highest [3]. The following parameters have been used in this study: $a_k = 2000\ N/m$; $b_k = 4.55\ kNT^{-1}m^{-1}$; $a_\xi = 0.15$; $b_\xi = 0.6364\ T^{-1}$; $B_S = 0.11\ T$.

3. MRE isolator

The model used in this section is a single d.o.f. isolator (Fig. 1), subjected to a narrow band harmonic excitation. It consists of a spring with a MRE at one of its end, like in some advanced car suspension systems [8, 9]. The dynamics of the system read

$$m_s\ddot{x}_s + c(\dot{x}_s - \dot{x}_1) + k(x_s - x_1) = 0 \quad ; \quad c(\dot{x}_s - \dot{x}_1) + k(x_s - x_1) = k_1(x_1 - x_0) \tag{2}$$

where m_s is the mass of the oscillator, k_1 is the stiffness of the isolator spring, k and $c = 2\xi\sqrt{km_s}$ the equivalent stiffness and damping coefficients of the elastomer given by Equ.(1). The numerical values used in this study are $m_s = 100\ kg$ and $k_1 = 100\ kN/m$.

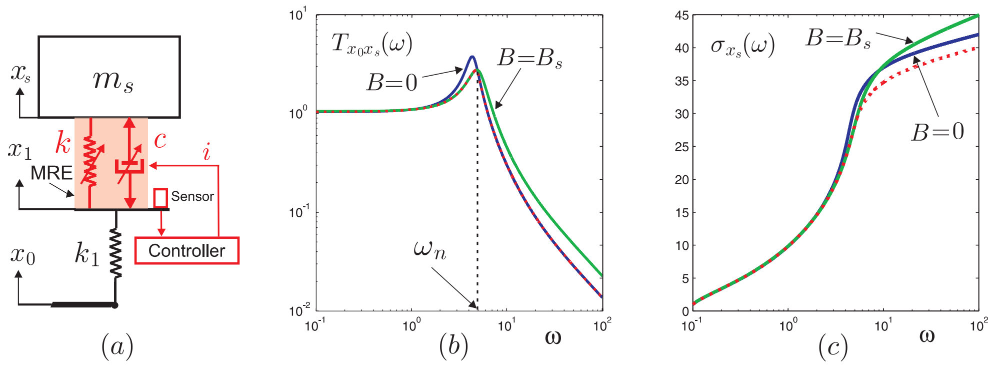

Figure 1. (a) Model of MRE isolator; (b) Transmissibility $T_{x_0x_s}(\omega)$ and (c) RMS value $\sigma_{x_s}(\omega)$ of a MRE isolator for two values of B: $B = 0$ (blue curve) and $B = B_s$ (green curve).

Consider a periodic chirp excitation with a unit amplitude applied in x_0. Figure 1(b) shows the absolute value of the transmissibility $T_{x_0x_s}(\omega)$ of the isolator for two extremal values of the magnetic field : $B = 0$ (blue curve) and $B = B_s$ (green curve). Figure 1(c) shows the cumulative Root Mean Square (RMS) integral of the transmissibilities defined as

$$\sigma_{x_s}(\omega) = \left[\int_0^\omega |T_{x_0x_s}(\nu)|^2 d\nu\right]^{1/2} \tag{3}$$

which describes how the various frequencies contribute to the RMS of the mass displacement. When the frequency of the excitation is lower than ω_n, the transmissibility obtained for $B = B_s$ is the lowest; above this value, $B = 0$ gives the lowest transmissibility. This suggests the following control strategy:

$$\begin{array}{llll} \text{IF} & \omega \leq \omega_n & \text{THEN} & B = B_s \\ \text{IF} & \omega > \omega_n & \text{THEN} & B = 0 \end{array}$$

The control strategy is implemented and shown as a dotted red line in Fig. 1. Figure 1(c) shows that the frequency shift can reduce the RMS value of the mass displacement by 10%.

4. MRE Dynamic Vibration Absorber

Consider a n-storey frame subjected to a horizontal base excitation of acceleration $\ddot{x}_0$. The variables of the system are the lateral displacements of each stage $x = (x_1, ..., x_n)^T$. The mass and stiffness matrices are respectively $M = mI_n$ and

$$K = k_S \begin{pmatrix} 2 & -1 & & & \\ -1 & 2 & & & \\ & & \ddots & & \\ & & & 2 & -1 \\ & & & -1 & 1 \end{pmatrix} \quad (4)$$

and I_n is the identity matrix of dimension n.

Consider a DVA attached on floor d and tuned to mode k. According to the equal peak design procedure [10], it can be shown that the optimal values of the stiffness and damping coefficient of the DVA are given by

$$k_a = m_a \left[\omega_k/(1+\lambda)\right]^2 \quad ; \quad \xi_a = \sqrt{3\lambda/[8(1+\lambda)]} \quad (5)$$

where $\lambda = \frac{m_a}{\mu_k}\phi_k^2(d)$, μ_k and ϕ_k respectively the mass and shape of mode k. In such a structure subjected to a seismic excitation, a relevant quantity is the shear force at the base, given by $F_0 = k_s(x_1 - x_0)$. In the numerical example, $m = 10\ kg,\ k_s = 750\ kN/m,\ d = 7,\ m_a = 1\%$ of the total mass ($m_T = 7m$ in this case) and $k = 1$. Using Equ.(5), the optimal values of the stiffness and damping coefficient of the DVA are $k_a = 2620\ N/m$ and $\xi_a = 0.09$. Unfortunately, for an actual material, it is not possible to choose independently the stiffness and damping coefficient. Choosing a stiffness of $k_a = 2620\ N/m$ gives automatically a damping of $\xi_a = 0.23$ (data from [3]). As this value is greater than the optimal value, the DVA is over-damped, providing a lower efficiency than the optimal case. Now consider that the mass of each storey of the structure increases from $m = 10\ kg$ to $m = 13.5\ kg$. Three cases are compared: (i) a DVA with constant properties, optimal for $m = 10\ kg$; (ii) a fictive DVA that would have optimal values for both the stiffness and damping coefficient; (iii) a MRE DVA. Figure 2 (a) to (d) compare respectively the stiffness and damping of the DVA, the reduction ($\Delta\sigma$) of the RMS value of the shear force at the base of the frame

$$\sigma_{F_0} = \left[\int_0^\infty |T_{x_0F_0}(\omega)|^2 d\omega\right]^{1/2} \quad (6)$$

and the reduction (ΔT) of the maximum value of the transmissibility $|T_{x_0F_0}|$ calculated in dB.

As the mass of the structure increases, the DVA with constant properties is not tuned to the first resonance anymore, and ΔT and $\Delta\sigma$ decrease rapidly. The fictive DVA maintains $\Delta\sigma$ above 45% and $\Delta T = 15\ dB$. The MRE DVA, while not optimal for a structure with constant properties, maintains $\Delta\sigma$ at 41 % and $\Delta T = 11\ dB$ throughout the range. Similar results are presented in Fig. 2(a' to d') when the mass of each storey decreases from $m = 13.5\ kg$ to $m = 10\ kg$.

5. Conclusion

In this paper, the isolation and damping properties of the magnetorheological elastomer have been investigated for two cases. Firstly, a single d.o.f. isolator, was subjected to a narrow band excitation. It has been shown that the MRE isolator can decrease the RMS value of the body displacement by 10 %. Secondly, a n-storey mass-varying structure has been considered, on which is appended a MRE DVA. A proper application of the magnetic field to the MRE can maintain a good efficiency compared to a classical DVA. The adaptability is particularly suited for structures whose mass and/or stiffness is varying in a fixed range of values.

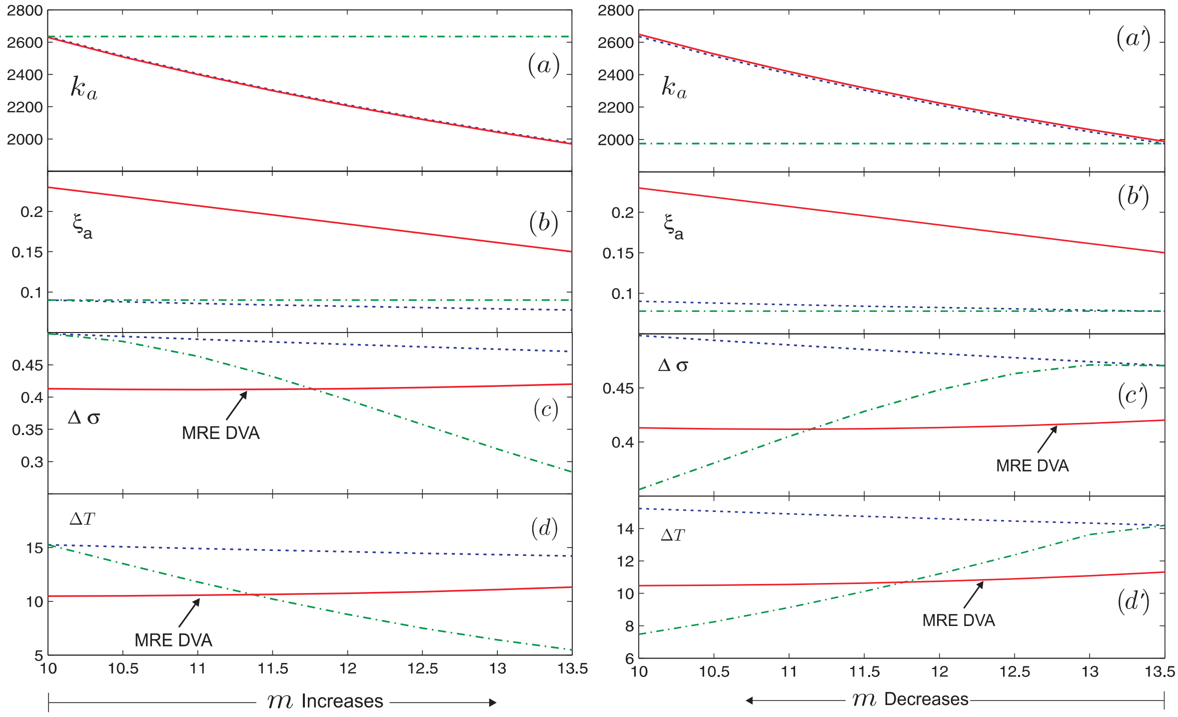

Figure 2. Comparison between three DVAs appended on a mass-varying structure: DVA with constant properties (dashed dotted line), DVA with optimally tunable properties (dotted line), and MRE DVA (solid line). (a, a') Stiffness of the DVA; (b, b') Damping coefficient of the DVA; (c, c') Reduction of the RMS value of the shear force at the base of the structure; (d, d') Reduction of the maximum amplitude of the shear force to excitation transmissibility $|T_{x_0F_0}|$.

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