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Comparison of vibration control performance between flow and squeeze mode ER mounts: Experimental work

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Abstract

This paper proposes two different electrorheological (ER) mounts and compares vibration control performance. Dynamic models of flow and squeeze mode mounts are formulated and design parameters are determined by considering a static load of 200 kg. After manufacturing two ER mounts, the field-dependent displacement transmissibilities are evaluated in frequency domain. A simple sky-hook controller is then designed to attenuate the imposed vibration and the controller is experimentally realized. Vibration control responses are evaluated in frequency domain and compared between the flow and squeeze mode ER mounts.

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1. Introduction

One of the attractive approaches to attenuate unwanted vibration of dynamic systems is to utilize an electro-rheological (ER) fluid mount (ER mount in short). When the ER mount is used for vibration control, the operating mode of the mount can be classified into three different types: flow mode, shear mode, and squeeze mode. In the flow mode, it is assumed that two electrodes are fixed, and hence vibration control is achieved by controlling the flow motion between two fixed electrodes [1–4]. In the shear mode, it is usually assumed that one of two electrodes is free to translate or rotate relative to the other, and hence vibration control is achieved by controlling

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shear force between two electrodes [5–7]. Unlike the former two modes, in the squeeze mode the electrode gap is varied and the ER fluid is squeezed by a normal force. Controlling the normal force (or squeeze force), an effective vibration control can be achieved [8,9]. Each mode, of course, has its inherent characteristics.

A typical ER mount for passenger vehicles is normally designed to support a static load of 70 kg in the three-point pivot. In this case, it is relatively easy to fabricate the ER mount since a short electrode length and a small number of electrode gaps can be chosen. Furthermore, the electrode gap is easily maintained to be constant during the dynamic motion by employing a linear bearing. However, we can expect more difficulties in manufacturing ER mount, which can be used for vibration control of dynamic systems subjected to higher capacity of the static load. The main contribution of this work is to propose two different types of ER mounts (flow mode and squeeze mode) which can support a static load of 200 kg, and hence to evaluate and compare vibration control performance. In order to achieve this goal, two ER mounts are designed and manufactured. The field-dependent displacement transmissibilities are then evaluated in the frequency domain. A simple skyhook controller is formulated to attenuate the imposed vibration and experimentally implemented. Vibration control responses of two ER mounts are evaluated and compared. It is noted that none deals with a comparative work of two different types of ER mounts, which can support a static load of 200 kg.

2. Manufacturing of ER mounts

The configuration of the flow mode ER mount proposed in this work is shown in Fig. 1(a). Multicylindrical electrodes are fixed to the housing, and the flow motion occurs between the upper and lower chambers. Thus, the ER mount shown in Fig. 1(a) is a flow mode type. The main rubber part is designed to support a static load of 200 kg. In this work, we consider only the vertical motion of the mount for simplicity. The governing equation of the flow mode ER mount can be easily derived as follows [10]:

$$M\ddot{x}(t) = -K_R(x(t) - y(t)) - B_R(\dot{x}(t) - \dot{y}(t)) + A_p P_1(t), \tag{1}$$

where M is the static load, K_R is the stiffness of the main rubber, B_R is the damping constant of the main rubber, A_P is the area of the upper chamber, $P_1(t)$ is the pressure of the upper chamber, $x(t)$ is the displacement of the load, and $y(t)$ is the input(excitation) displacement. On the other hand, the pressure drop due to the ER fluid passing through the electrode gaps can be given by

$$P_2(t) - P_1(t) = I_i\dot{Q}_i(t) + R_i Q_i(t) + \Delta P_{\mathrm{ERf}}(E(t)), \tag{2}$$

where

$$\Delta P_{\mathrm{ERf}}(E(t)) = 2\frac{L_e}{h_e}\tau_y(E(t))\,\mathrm{sgn}\,(Q_i(t)).$$

In the above, $P_2(t)$ is the pressure of the lower chamber, $\Delta P_{\mathrm{ERf}}(E(t))$ is the pressure drop due to the yield stress of the ER fluid, I_i is the fluid inertia, R_i is the flow resistance due to the viscosity, and $Q_i(t)$ is the flow due to the pressure difference between the upper and lower electrodes. L_e is the electrode length, h_e is the electrode gap, $\tau_y(E(t))$ is the yield shear stress of ER fluid, and $E(t)$ is

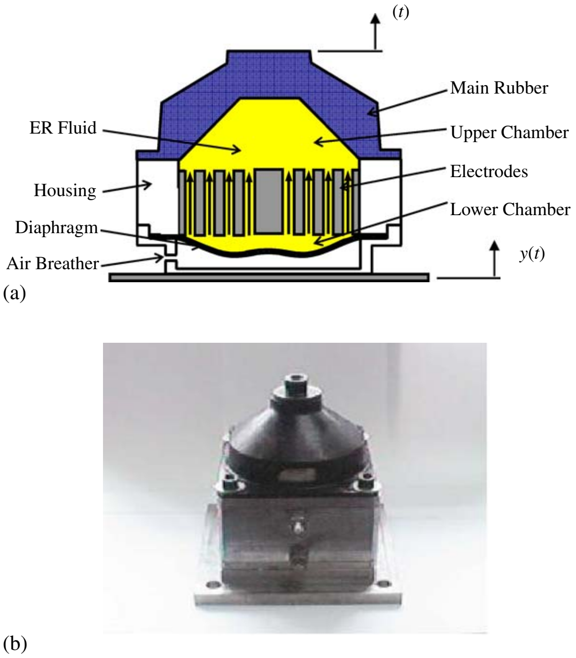

Fig. 1. The proposed flow mode ER mount: (a) configuration, (b) photograph.

the electric field applied to the gap. By considering the continuity equation for the flow at upper and lower chambers, Eqs. (1) and (2) are represented by [10]

$$M\ddot{x}(t) = -(K_R + K_{pp1})(x(t) - y(t)) - B_R(\dot{x}(t) - \dot{y}(t)) + K_{ip1}x_i(t), \tag{3}$$

$$M_i\ddot{x}_i(t) = -B_i\dot{x}_i(t) - (K_{ip1} + K_{ip2})x_i(t) + K_{pp1}(x(t) - y(t)) - F_{\mathrm{ERf}}(t), \tag{4}$$

where

$$Q_i(t) \equiv A_i\dot{x}_i(t),\ \ K_{pp1} \equiv \frac{A_p^2}{C_1},\ \ K_{ip1} \equiv \frac{A_iA_p}{C_1},\ \ K_{ip2} \equiv \frac{A_iA_p}{C_2},\ \ M_i \equiv I_iA_iA_p,$$

$$B_i \equiv R_iA_iA_p, F_{\mathrm{ERf}}(t) \equiv A_p\Delta P_{\mathrm{ERf}}(E(t)) \equiv 2A_p\frac{L_e}{h_e}\tau_y(E(t))\mathrm{sgn}(\dot{x}_i(t)).$$

In the above, $x_i(t)$ is the displacement of fluid flow through the gap and A_i is the cross-sectional area of the gap. C_1 and C_2 represent compliance of the upper and lower chamber, respectively. It can be observed from the above governing equations that both the stiffness and damping properties of the ER mount can be tuned by the yield shear stress of ER fluid.

For the evaluation of the field-dependent pressure drop, an ER fluid consisting of chemically treated starch particles and silicone oil has been prepared and its yield stress has been experimentally obtained by $\tau_y(E(t)) = \alpha E(t)^{\beta} = 699E(t)^{1.31}$ Pa. Here, the unit of the electric field $E(t)$ is kV/mm. The detailed measurement procedure of the yield stress can be found from Ref. [11]. After analyzing the dynamic model associated with the field-dependent yield stress, an appropriate size of ER mount which can support the static load of 200 kg was designed and

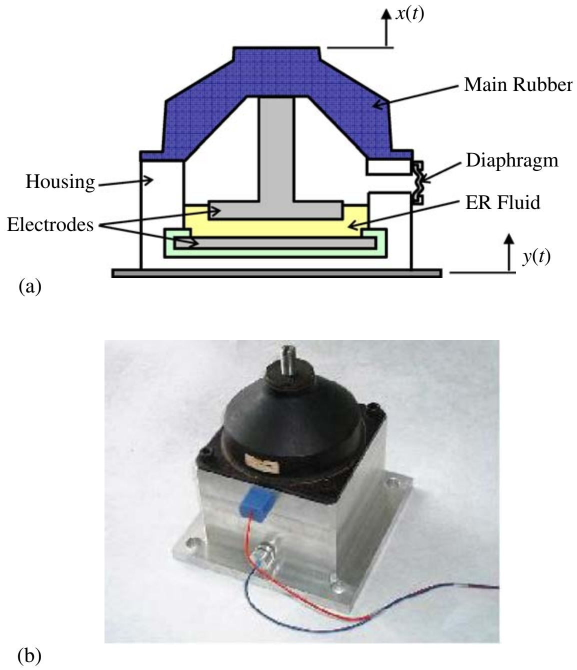

Fig. 2. The proposed squeeze mode ER mount: (a) configuration, (b) photograph.

manufactured as shown in Fig. 1(b). The principal design parameters are given as follows: electrode length = 30 mm, electrode gap = 1.5 mm, and the number of electrode gaps = 8.

The schematic configuration of the squeeze mode ER mount proposed in this study is shown in Fig. 2(a). The lower electrode is fixed to the base plate, while the upper electrode is to be moved up and down. By the motion of the upper electrode, the ER fluid flows radially through the disc gap between upper and lower electrodes. If no electric field is applied, the ER mount produces a damping force only caused by the fluid resistance associated with the viscosity of the ER fluid. However, if a certain level of electric field is applied through the gap between electrodes, the ER mount produces an additional damping force owing to the yield stress of the ER fluid. The main rubber part is designed to support a static load of 200 kg. Similar to the flow mode ER mount, we consider only the vertical motion of the mount. The damping force $F_d(t)$ of the squeeze mode ER mount due to the fluid flow resistance can be expressed by [12]

$$F_d(t) = B_s(t)(\dot{x}(t) - \dot{y}(t)) + F_{\mathrm{ERs}}(t), \tag{5}$$

where

$$B_s(t) = \frac{3}{2}\frac{\pi\eta R^4}{(h_0 + x(t) - y(t))^3}, \quad F_{\mathrm{ERs}}(t) = \frac{3}{4}\frac{\pi R^3}{h_0 + x(t) - y(t)}\tau_y(E)\,\mathrm{sgn}\,(\dot{x}(t) - \dot{y}(t)).$$

In the above, R is the outer radius of the disk type electrodes, $B_s(t)$ is the damping constant associated with the viscous flow resistance, and $F_{\mathrm{ERs}}(t)$ is the controllable damping force owing to the ER effect under the squeeze motion. The governing equation of the squeeze mode ER mount can be derived by

$$\begin{aligned} M\ddot{x}(t) &= -K_R(x(t)-y(t)) - B_R(\dot{x}(t)-\dot{y}(t)) - F_d(t) \\ &= -K_R(x(t)-y(t)) - (B_R + B_s(t))(\dot{x}(t)-\dot{y}(t)) - F_{\mathrm{ER}s}(t). \end{aligned} \tag{6}$$

As it can be seen from Eqs. (5) and (6), the damping of the squeeze mode ER mount can be tuned by the yield shear stress of ER fluid. After analyzing the governing Eq. (6), an appropriate size of the ER mount is manufactured as shown in Fig. 2(b)). The radius of the circular electrode is designed to be 50 mm and the initial gap is set by 3 mm. It is noted that the main rubber of the squeeze mode ER mount is same as that of the flow mode ER mount.

3. Control characteristics

In order to evaluate vibration control performance of the proposed ER mounts, an experimental apparatus is established as shown in Fig. 3. The mass of 200 kg fixed on the ER mount is excited by a motor-cam system. The excitation frequency is varied up to 30 Hz with the excitation amplitude of ±0.1 mm. The excitation amplitude is measured by a proximitor, while the displacement of the mass by the linear variable differential transducer (LVDT). On the other hand, in the closed-loop control action the signal from the LVDT is fed back to the microcomputer via analog-to-digital (A/D) converter, and an appropriate control voltage is applied to the ER mount via digital-to-analog (D/A) converter and a high voltage amplifier, which has a gain of 1000. The sampling frequency in the controller implementation is chosen to be 2 kHz.

Fig. 4 presents the measured displacement transmissibility of the ER mounts at various electric fields. The displacement transmissibility is obtained by dividing the amplitude (x) of the mass displacement by the amplitude (y) of the excitation magnitude. It is observed from Fig. 4(a) that transmissibility magnitude of the flow mode ER mount is slightly reduced by applying the electric field of 0.5 kV/mm. But the peak value of the transmissibility is not lowered by the electric fields of higher than 1.0 kV/mm. Instead, its peak is shifted to the right. This is due to the lock-up state in which the flow motion does not take place. The lock-up state occurs if the pressure difference between the upper and lower chamber is smaller than the pressure drop due to the yield stress;

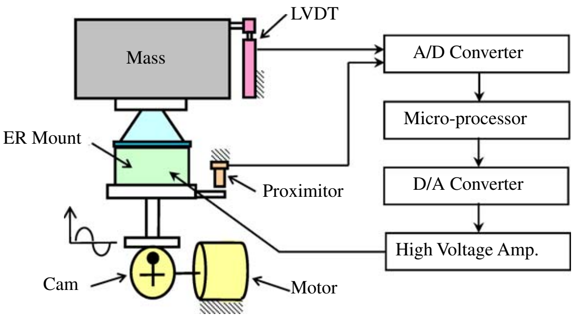

Fig. 3. Experimental apparatus for the ER mount test.

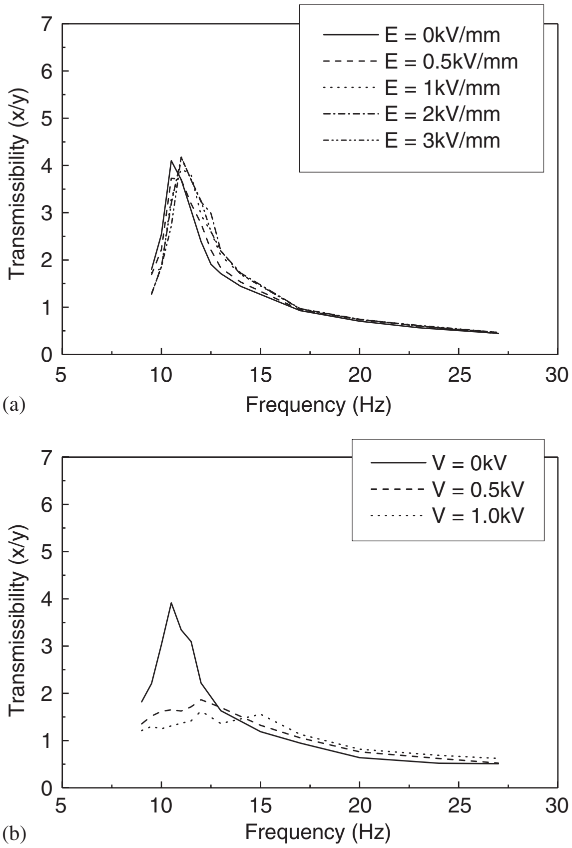

Fig. 4. Field-dependent displacement transmissibility: (a) flow mode, (b) squeeze mode.

$\dot{x}_i(t) = 0$, if $|P_2(t) - P_1(t)| < \Delta P_{\mathrm{ERf}}(E(t))$. Therefore, when the ER fluid cannot flow through gaps, the damping due to the fluid flow resistance cannot be available and overall stiffness of the flow mode ER mount increases.

On the other hand, the transmissibility of the squeeze mode ER mount shown in Fig. 4(b) is significantly reduced in the neighborhood of the resonance frequency as the electric field increases. Since the significant reduction of the transmissibility at the resonance has been obtained by applying 1 kV, the higher voltage has not been applied to the squeeze mode ER mount.

In order to achieve an effective vibration attenuation in the wide frequency range, a skyhook controller which is known to be very efficacious for a semi-active mount is adopted [13]. The control input which directly represents the controllable damping force is set by

$$F_{\mathrm{ERf}}(t) = c_{\mathrm{skyf}}\dot{x}(t) \quad \text{for the flow mode,} \tag{7}$$

$$F_{\mathrm{ERs}}(t) = c_{\mathrm{skys}}\dot{x}(t) \quad \text{for the squeeze mode,} \tag{8}$$

where c_{skyf} and c_{skys} are the constant gains for the flow and squeeze mode ER mounts, respectively. These physically imply damping coefficients.

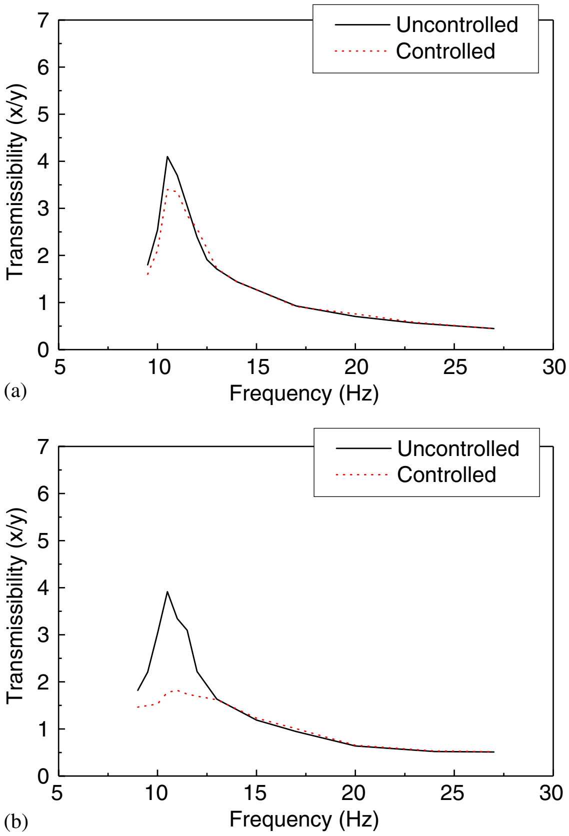

Fig. 5. Control responses of the ER mounts: (a) flow mode, (b) squeeze mode.

Fig. 5 presents control responses of the proposed ER mounts. It is shown that the displacement transmissibility of each ER mount can be reduced by applying control input field to the ER fluid domain. Especially, the performance deterioration of the flow-mode mount due to the lock-up state is resolved by the implementation of the skyhook controller. It is known that as the sky-hook gain increases, the peak value of transmissibility decreases [13]. However, the value of the control gain should be appropriately determined by considering the limit of the electric field as well as performance improvement. This is normally done through experimental trial-error procedure. The sky-hook gains c_{skyf} and c_{skys} used in this work are 3000 and 4000, respectively. Since the operating mechanisms of the flow and squeeze mode ER mounts are different, the sky-hook gains for each mount are chosen differently. It is clearly observed that the squeeze mode ER mount exhibits better control response in the neighborhood of the resonance frequency. This is because the squeeze mode ER mount does not exhibit lock-up phenomenon under small magnitude excitation conditions, while the flow mode ER mount approaches easily to lock-up status when the excitation magnitude is small. It is noted that the lock-up mode is directly related to the increment of the stiffness of the mount system. The increment of the stiffness of the flow mode mount is higher than that of the squeeze mode mount in the presence of the same field intensity. The results presented in this work suggest that the squeeze mode ER mount is very effective for vibration attenuation in which the imposed excitation has a relatively small magnitude such as ±0.1 mm.

4. Concluding remarks

Two types of electrorheological (ER) mounts, which can be adaptable to dynamic systems subjected to a high capacity of the static load (200 kg), were proposed and their control performances were experimentally evaluated and compared. It has been demonstrated that the displacement transmissibility of the proposed ER mounts can be effectively reduced by implementing the skyhook controller. In addition, it was shown that the squeeze mode ER mount is more effective than the flow mode one in the low level excitation. The potential applications of the proposed ER mounts for vibration control include diesel engines, electric power supply units, and elastic decks of electronic equipments. Sophisticated dynamic modeling and robust control of the proposed two different ER mounts will be undertaken in the near future.

Acknowledgements

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