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# VIBRATION CONTROL OF AN ER MOUNT SUBJECTED TO HIGH STATIC LOADS

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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 which undergoes instantaneous and reversible change in rheological properties when subjected to applied electric potentials. So far, much of the research on ER engine mount has been undertaken in order to control unwanted vibration of passenger vehicles [1–5]. A typical ER engine mount for a small-sized passenger vehicle 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 we can choose short electrode length and small number of electrode gap. This, of course, is possible due to the fact that commercially available ER fluid exhibits sufficient level of the field-dependent yield stress to take into account the static load of 70 kg. Furthermore, the electrode gap size 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.

Consequently, the main contribution of this work is to propose a flow mode type ER mount which can support a static load of 200 kg, and hence is to show vibration control effectiveness of proposed mount system. After analyzing the governing equation of motion, an appropriate size of the ER mount is designed and manufactured. The field-dependent displacement and acceleration transmissibilities are evaluated in the frequency domain. In addition, controlled responses of the proposed ER mount associated with a skyhook controller are experimentally investigated and compared with those of an equivalent rubber mount.

## 2. DYNAMIC MODEL

The proposed ER mount has a configuration as shown in Figure 1(a). Multi-cylindrical electrodes are fixed to the housing, and the flow motion occurs between the upper and lower

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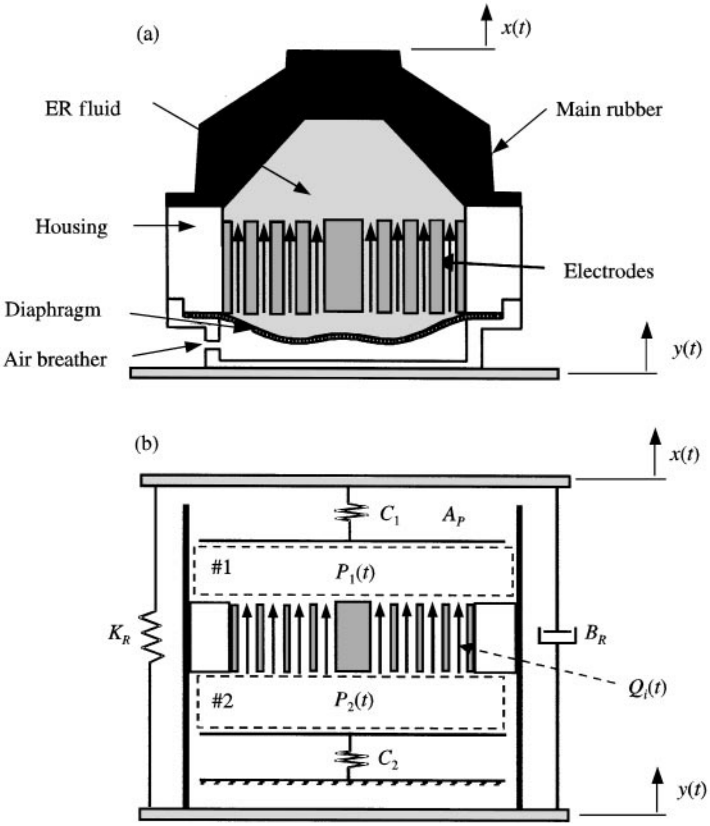

Figure 1. Configuration of the proposed ER mount: (a) schematic diagram; (b) hydraulic model.

chambers. Thus, the proposed ER mount 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.

From the hydraulic model shown in Figure 1(b), the following equation of motion is derived:

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

where $M$ is the static load, $K_R$ the stiffness of the main rubber, $B_R$ the damping constant of the main rubber, $A_P$ the area of the upper chamber, $P_1(t)$ the pressure of the upper chamber, $x(t)$ the displacement of the load, and $y(t)$ 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

$$P_2(t) - P_1(t) = I_i\dot{Q}_i(t) + R_iQ_i(t) + \Delta P_{ER}(t), \qquad (2)$$

where

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

In the above equation $P_2(t)$ is the pressure of the lower chamber, $\Delta P_{ER}(t)$ pressure drop due to the yield stress of the ER fluid, which is a function of applied electric field $E$, $Q_i(t)$ the flow due to the pressure difference between the upper and lower chambers, $I_i$ the fluid inertia, $R_i$ the flow resistance in the absence of the electric field, $L_e$ the electrode length and $h_e$ the electrode gap. Now, by considering the continuity equation for flow at upper and lower chambers, the following equations are obtained [6]:

$$C_1\dot{P}_1(t) = Q_i(t) + A_P(\dot{x}(t) - \dot{y}(t)), \tag{3}$$

$$C_2\dot{P}_2(t) = -Q_i(t), \tag{4}$$

where $C_1$ and $C_2$ represent compliance of the upper and lower chambers, respectively. From equations (1) and (4), we can eliminate $P_1(t)$ and $P_2(t)$, and hence the following governing equations of motion are derived:

$$M\ddot{x}(t) = -(K_R + K_{pp1})(x(t) - y(t)) - B_R(\dot{x}(t) - \dot{y}(t)) + K_{ip1}x_i(t), \tag{5}$$

$$M_i\ddot{x}_i(t) = -B_i\dot{x}_i(t) - (K_{ip1} + K_{ip2})x_i(t) + K_{pp1}(x(t) - y(t)) - F_{ER}(t), \tag{6}$$

where

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

$$M_i \equiv I_iA_iA_p, \quad B_i \equiv R_iA_iA_p, \quad F_{ER}(t) \equiv A_p\Delta P_{ER}(t) \equiv 2A_p\frac{L_e}{h_e}\tau_y(E)\,\mathrm{sgn}(\dot{x}_t(t)).$$

We can observe from the above governing equations that both stiffness and damping properties of the ER mount can be tuned by the electric field. If the pressure difference between the upper and lower chamber is smaller than the pressure drop due to the yield stress of the ER fluid, the flow motion through the electrode gaps does not take place. This is called lock-up state. Thus, in this lock-up state; equation (6) becomes

$$\dot{x}_i(t) = 0 \quad \text{if}\, |P_2(t) - P_1(t)| < \Delta P_{ER}(t) \tag{7}$$

*In this work, chemically treated starch and silicone oil are used as particles and base oil, respectively, for the composition of the ER fluid. The field-dependent yield stress is measured under flow mode, and it is obtained by* $\tau_y(E) = 699E^{1\cdot31}$ Pa. Here the unit of the electric field $E$ is kV/mm. 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 is designed and manufactured as shown in Figure 2. The principal design parameters are given as follows: $L_e = 30$ mm, $h_e = 1\cdot5$ mm, $A_p = 5000\ \mathrm{mm}^2$, and the number of electrode gap = 8.

## 3. PERFORMANCE EVALUATION

In order to evaluate vibration control performance of the proposed ER mount, an experimental apparatus is established as shown in Figure 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 two different excitation amplitudes: ±1·0 and ±0·1 mm. The excitation amplitude is measured by a proximitor, while the displacement of the mass by the linear variable difference transducer (LVDT). An accelerometer is installed on the mass in order to evaluate acceleration transmissibility. On the other hand, in the closed-loop control action the signals from the LVDT and the accelerometer are fed back to the microcomputer via analog-to-digital (A/D) converter, and an appropriate control voltage is applied to the ER

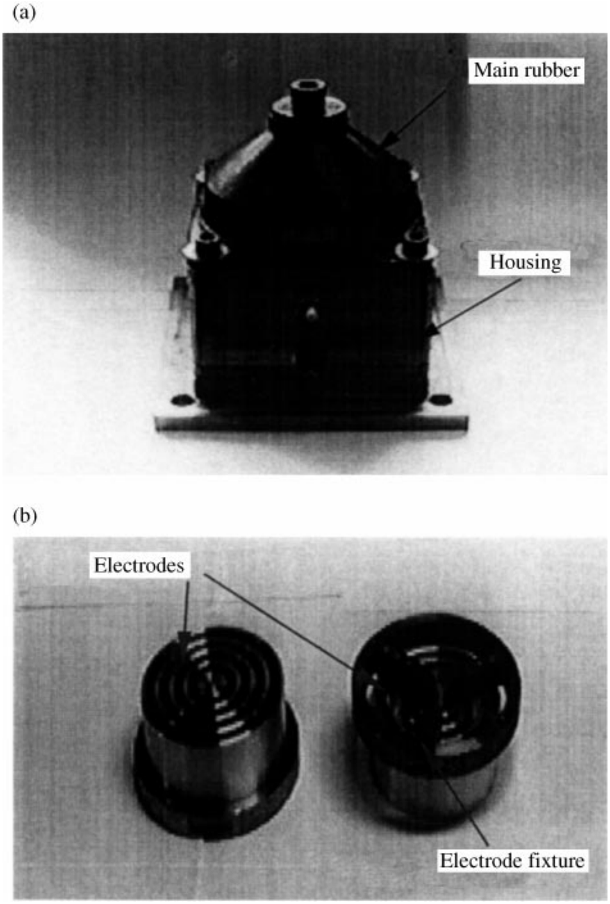

Figure 2. Photograph of the manufactured ER mount: (a) assembly; (b) electrode parts.

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.

Figure 4 presents the measured transmissibility of the ER mount when excited by the amplitude of ±1·0 mm. It is clearly observed that both the displacement and the acceleration transmissibilities are reduced in the neighborhood of the resonance frequency (7·5 Hz) as the electric field is increased. However, the performance exhibits different characteristics in the frequency range of 10–20 Hz. Therefore, an appropriate control algorithm needs to be implemented to improve the performance in the wide frequency range. Figure 5 presents the measured transmissibility at excitation magnitude of ±0·1 mm. Unlike the results shown in Figure 4, both transmissibilities are increased as the electric field is increased. This is due to the lock-up state. Therefore, a small magnitude of the electric field should be applied to the ER mount to avoid the lock-up state. This can be autonomously accomplished by realizing a closed-loop control.

In this work, a skyhook controller which is known to be very effective for a semi-active vibration control is adopted [7]. The control input which directly represents the controllable damping force is set by

$$u(t) = c_{sky}\dot{x}(t) = F_{ER}(t), \tag{8}$$

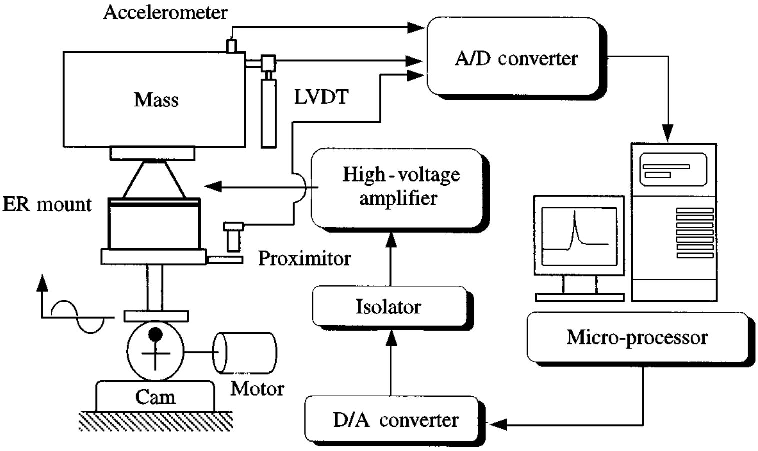

Figure 3. Experimental apparatus for the ER mount test.

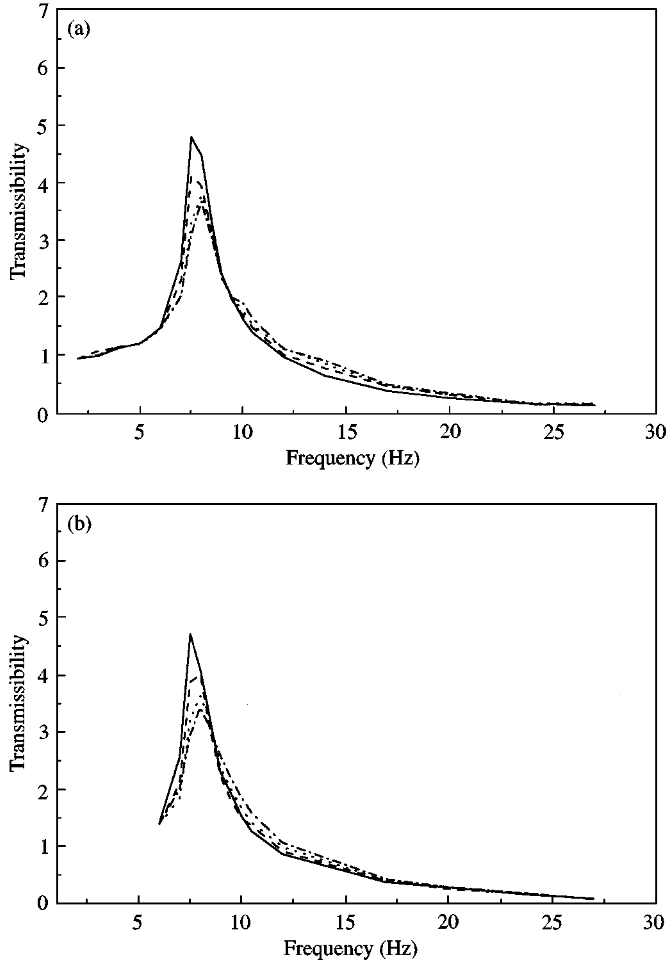

Figure 4. Field-dependent transmissibility at excitation amplitude of ±1·0 mm. (a) Displacement; (b) acceleration. ——, $E = 0$ kV/mm; - - - -, $E = 1$ kV/mm; · · · ·, $E = 2$ kV/mm; -·-·-· $E = 3$ kV/mm.

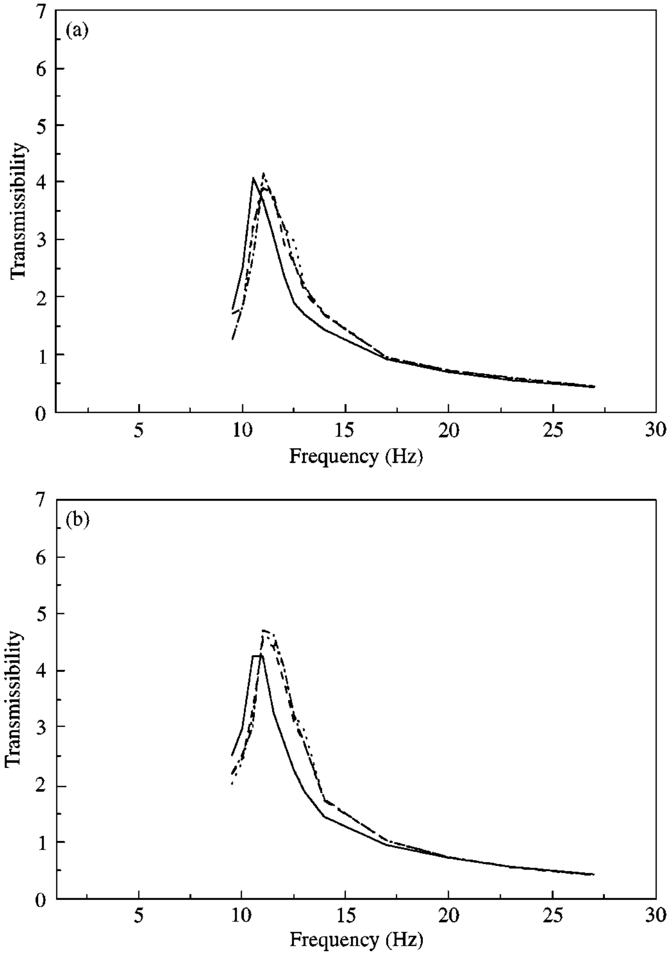

Figure 5. Field-dependent transmissibility at excitation amplitude of ±0·1 mm. (a) Displacement; (b) acceleration. ——, $E = 0$ kV/mm; - - - -, $E = 1$ kV/mm; · · · ·, $E = 2$ kV/mm; -·-·-· $E = 3$ kV/mm.

where $c_{sky}$ is the constant gain. This physically implies the damping coefficient. The damping force should be applied depending upon the relative motion to ensure the semi-active condition given by

$$u(t) = \begin{bmatrix} u(t) & \text{for } \dot{x}(t)(\dot{x}(t) - \dot{y}(t)) > 0, \\ 0 & \text{for } \dot{x}(t)(\dot{x}(t) - \dot{y}(t)) \leqslant 0. \end{bmatrix} \tag{9}$$

This condition physically indicates that the actuating of the controller $u(t)$ only assures the increment of energy dissipation of the stable system. Once the control input $u(t)$ is determined, the input electric field to be applied to the ER mount is obtained by

$$E(t) = \left( \frac{h_e}{1398 L_e A_P} u(t) \right)^{1/1 \cdot 31}. \tag{10}$$

Figures 6 and 7 compare the measured transmissibilities. We clearly see that both the displacement and acceleration transmissibilities at excitation magnitudes of ±1·0 and

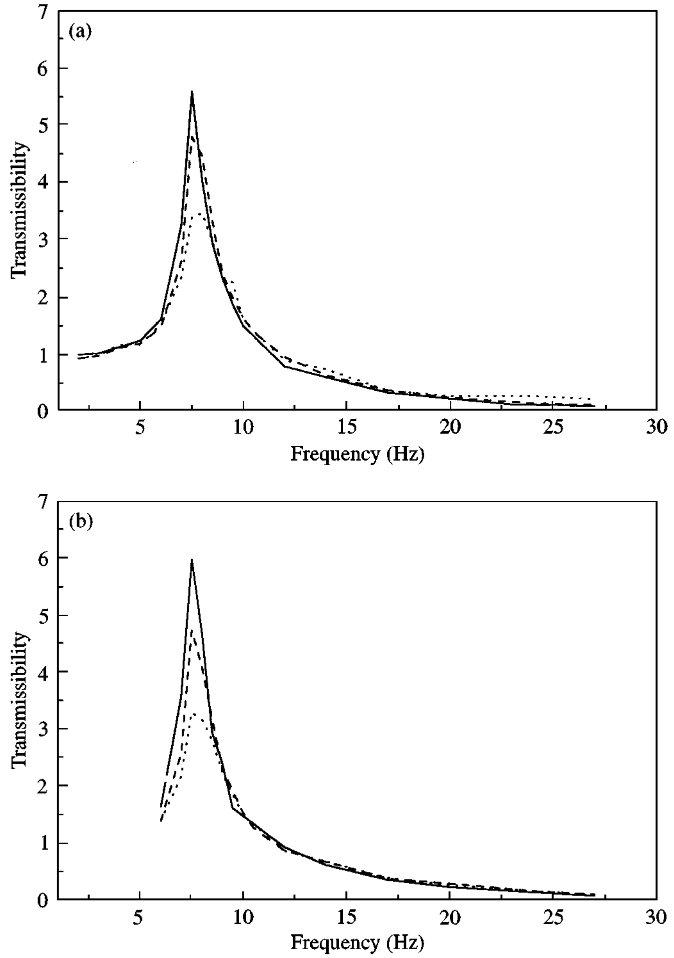

Figure 6. Controlled transmissibility at excitation amplitude of ±1·0 mm. (a) Displacement; (b) acceleration. ——, rubber mount; - - - -, uncontrolled ER mount; · · · ·, controlled ER mount.

±0·1 mm are substantially reduced in the neighborhood of the resonance frequency by employing the skyhook controller. It is remarked that the uncontrolled response of the ER mount is obtained in the absence of the electric field. We also see from Figure 7 that the performance deterioration due to the lock-up state is resolved by implementing the skyhook controller. In addition, it is observed that the proposed ER mount exhibits superior vibration attenuation performance in the resonance frequency to an equivalent conventional rubber mount. The conventional rubber mount adopted in this work is one of commercially available products made by Vibrachoc company in France.

## 4. CONCLUDING REMARKS

A flow mode electro-rheological (ER) mount, which can be adaptable to dynamic systems subjected to a high capacity of the static load (200 kg), was proposed and its performance on

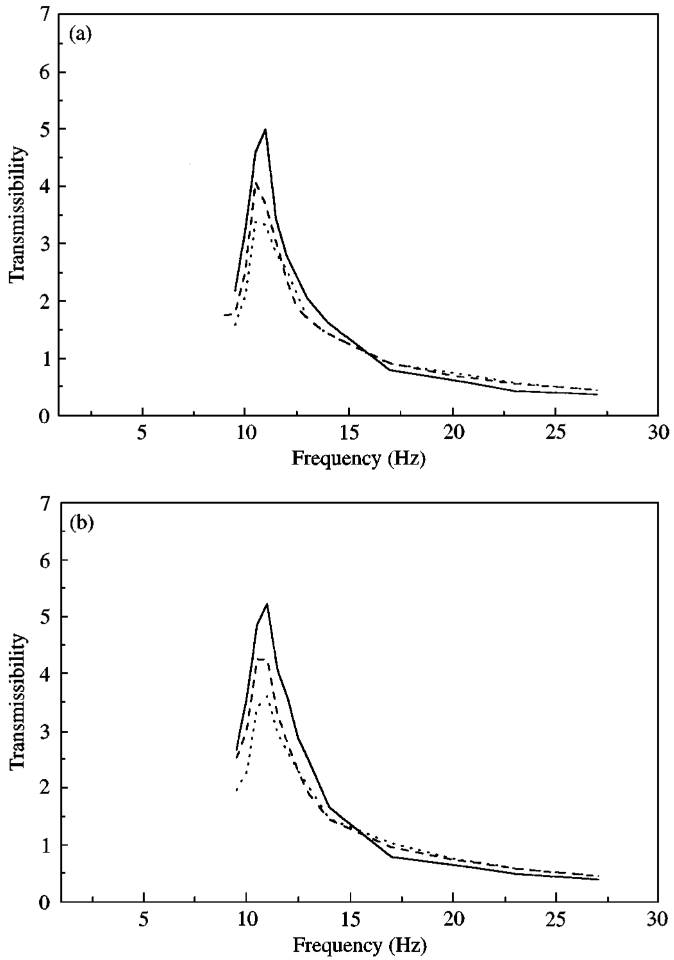

Figure 7. Controlled transmissibility at excitation amplitude of ±0·1 mm. (a) Displacement; (b) acceleration. ——, rubber mount; - - - -, uncontrolled ER mount; · · · ·, controlled ER mount.

vibration control was experimentally evaluated. It has been demonstrated that both the displacement and acceleration transmissibilities can be substantially reduced at the neighborhood of the resonance frequency by employing control electric field associated with the skyhook controller. The control results presented in this work directly indicate that we can devise an effective ER mount to attenuate unwanted vibration of dynamic systems subjected to high static loads. The potential applications of the proposed ER mount for vibration control include diesel engines, electric power supply units, and elastic decks of electronic equipments. Control performance in the relatively high frequency above the resonance frequency needs to be further explored.

## ACKNOWLEDGMENTS

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