Vibration Control of Squeeze Mode ER Mount Subjected to 200kg of Static Load

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Abstract
This paper presents vibration control performance of a squeeze mode ER mount for high static load. After experimentally investigating the field-dependent damping force under the squeeze mode motion, a squeeze mode ER mount which can support 200kg of static load is designed and manufactured. Displacement transmissibility of the proposed ER mount is experimentally evaluated in frequency domain with respect to the voltage, and a sky-hook control algorithm is designed to attenuate unwanted vibration. Also, transmitted forces of the proposed ER mount are numerically simulated in frequency domain. Vibration isolation capabilities of the flow mode ER mount and rubber mount are compared to those of the proposed squeeze mode ER mount.

I. Introduction
One of attractive approaches to attenuate unwanted vibration of dynamic systems is to utilize an electro-rheological fluid (ER fluid) which undergoes instantaneous and reversible changes in rheological properties when subjected to the electric field. So far, many researches on ER engine mount have been undertaken in order to control undesired vibration of passenger vehicles[1-5]. A typical ER engine mount for a small-sized passenger vehicle is normally flow mode type designed to support a static load of 70kg. 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 that commercially available ER fluid exhibits sufficient level of the field-dependent yield stress to take account for the static load of 70kg. Furthermore, the electrode gap size is easily maintained to be constant during the dynamic motion by employing a linear bearing. A flow mode ER mount is useful for large amplitude excitations that are principally observed in low frequency range[6]. 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 authors proposed flow mode ER mount available for supporting 200kg of static load[7].

In general, steady-state excitation amplitude of equipments is approximately lower than 0.1 ~ 0.2mm in the frequency range of above 20Hz. So, it is difficult to use flow mode ER mount in the frequencies upper than 20Hz for vibration reduction because of small amplitude of excitation. In the mounting system in ships, double stage mounting system or raft system is adopted for a more dynamically satisfactory performance of vibration isolation. In those mounting systems, there is an intermediate structure between upper and lower mounts to achieve required vibration reduction goal. Intermediate structure is massive and consisting of flexible structure members-beam and plate. Flexible structure has its own natural modes and this is the reason for large vibration and sound radiation in certain frequencies called resonance. It is necessary to control the resonance mode of flexible structure, especially 1st and 2nd mode which are offsetting the benefits associated with mounting system. Usually, resonance frequencies for 1st and 2nd bending mode are about 30~40Hz in most double mounting system or raft system. As the first application step of squeeze mode ER mount, small size of squeeze mode ER mount of 3kg static load was provided and applied to the vibration control of beam and frame structure by authors[8-9].

To meet the requirement of vibration control of massive system for small amplitude excitation in the higher frequencies, a squeeze mode ER mount of high static load is proposed in this paper. Consequently, the main contribution of this work is to propose a squeeze mode ER mount which is able to support a static load of 200kg, and hence is to show vibration control effectiveness of the proposed ER mount. After experimentally investigating the field-dependent damping force under the squeeze mode motion and analyzing the governing equation of motion, an appropriate size of the ER mount is designed and manufactured. The electric field-dependent displacement transmissibilities are experimentally evaluated in the frequency domain. Also,
numerical simulations of transmitted forces of ER mount are presented in frequency domain. In addition, controlled responses of the proposed ER mount associated with a skyhook controller are compared to those of the flow mode ER mount and rubber mount.

II. Bingham-Plastic Behavior

The behavior of ER fluid in the squeeze mode motion can be expressed by Bingham-plastic model as follows.

$$\tau = \tau_s(E) + \eta \dot{\gamma}, \quad \tau_s(E) = \alpha E^\beta$$

where $\tau$ is the shear stress, $\tau_s(E)$ the yield stress dependent on electric-field $E$, $\eta$ viscosity of ER fluid, $\dot{\gamma}$ strain rate. Also, $\alpha$ and $\beta$ are intrinsic values of the ER fluid to be experimentally determined. In this work, chemically treated starch and silicone oil are used for particles and base liquid, respectively, for the composition of ER fluid. Fig. 1 shows Bingham test apparatus to extract the value of $\alpha$ and $\beta$ for the squeeze flow. During the squeeze mode flow, total force measured in upper load cell is a sum of the electric field dependent force($F_{er}$) and non-electric field fluid damping force($F_\eta$) [9]. The initial gap between electrodes is 3mm. The exciting magnitude is fixed by $\pm 20 \mu m$, while the exciting frequency is 75Hz. Fig.2 presents the time response of measured damping force of ER fluid under the squeeze mode. In this response, total measured forces are 0.55N at 1kV, while, 2.3N at 4kV. The measured yield stress of ER fluid of the squeeze mode motion is illustrated in Fig. 3. We clearly observe from Fig. 2 and Fig. 3 that the yield stress is increased as the electric field increases. The following measured yield stress from Eqs. (1) is obtained:

$$\tau_s(E) = 437E^{1.2}, \quad \alpha = 437, \beta = 1.2, \eta = 0.08$$

Here the unit of the electric field $E$ is kV/mm

III. Dynamic Model of Squeeze Mode ER Mount

The schematic configuration and mathematical model of the ER mount proposed in this paper is shown in Fig. 4 and Fig. 5, respectively. The lower electrode is fixed to the base, while the upper electrode is to be moved up and down. Thus, the squeeze-mode motion of the ER fluid occurs in the housing. The rubber mount, which is EIN 101-04 made in France by Paulstra is attached to provide a static load capability of 200kg. The total force of the proposed ER mount can be obtained by

$$F(t) = k_x(x(t) - y(t)) + B_f(t)(\dot{x}(t) - \dot{y}(t)) + F_{er}(t)$$

where, $B_f(t) = B_s + B_{er}(t) = B_s + \frac{3}{2} \frac{\pi \eta R^4}{(h_o + (x(t) - y(t))^2)}$, $F_{er}(t) = \frac{4}{3} \frac{\pi R^3}{(h_o + (x(t) - y(t))^2)} \tau_s(E) \text{sgn}(\dot{x}(t) - \dot{y}(t))$.

In the above, $B_s, k_x, k_y$ are damping and stiffness coefficient of the rubber mount, $B_f(t)$ damping force coefficient of the ER fluid in the absence of the electric field, $x(t)$ the displacement of mass, $y(t)$ the input(excitation) displacement, $h_o$ initial gap between lower and upper electrodes, and $R$ radius of the circular electrode. $F_{er}(t)$ is controllable damping force owing to the electric field $E$. The controllable damping force increases as the initial gap, $h_o$ and relative vibration displacement $(x(t) - y(t))$ decrease.

From the mathematical model shown in Fig. 5, the following equation of motion for the squeeze mode ER mount is derived:

$$M \ddot{x}(t) = -F(t)$$

$$= -k_x(x(t) - y(t)) - B_f(t)(\dot{x}(t) - \dot{y}(t)) - F_{er}(t)$$

(4)

We can observe from the above governing equation that damping force of the squeeze mode ER mount can be tuned by the
electric field. After analyzing the dynamic model associated with field-dependent yield stress, an appropriate size of ER mount which can support the static load of 200kg is designed and manufactured according to flow chart as shown Fig. 6. The manufactured squeeze mode ER mount of 200kg static load is shown in Fig. 7 and Fig. 8. The outer size of proposed ER mount is W220mm x L220mm x H250mm. The initial gap between lower and upper electrodes, \( h_g \), is 3mm and radius of the circular electrode, \( R \), is 100mm

**IV. Vibration Control Performance**

**IV.1 Experimental Apparatus**

In order to evaluate vibration control performance of the proposed ER mount, an schematic diagram is established as shown in Fig. 9. The mass of 200kg fixed on the top of ER mount is only vertically excited guided by linear bearing in the upper part using a motor-cam system. Sinusoidal excitation wave is produced by eccentric cam which is installed at the rotating axis of driven motor (3-phase AC motor, 25HP). The excitation frequency is varied up to 30Hz with excitation amplitudes of \( \pm 100 \mu m \). The excitation amplitude and displacement of the mass are measured by two proximity sensors. On the other hand, in the closed loop control action, the signals from the two proximity sensors are used back to the microcomputer via A/D(analog-to-digital) converter, and an appropriate control voltage is applied to the ER mount via D/A(digital-to-analog) converter and a high-voltage amplifier which has a gain of 1000. The sampling frequency in the controller implementation is chosen to be 2KHz. A photograph of the employed experimental apparatus is shown in Fig. 10.

**IV.2 Performance Evaluation at Constant Voltage**

Fig. 11 shows the measured force-displacement relation in the 200kg squeeze mode ER mount for the excitation frequency of 10.5Hz. A small closed elliptic circle with some rotated angle relative to horizontal axis is developed when no voltage is applied. The reason for the inclined angle is due to the rubber mount which is responsible to support the 200kg of static load in the proposed squeeze mode ER mount. The area of the closed elliptic circle is increased as the voltage increases. The area of the closed elliptic circle means the energy dissipation capability of damping force to be used during operation. So, the damping force of the squeeze mode ER mount becomes larger as the area of the closed elliptic circle bigger.

Fig. 12 presents the measured displacement transmissibility of the ER mount when excited by the amplitude of \( \pm 100 \mu m \) with constant voltage. The displacement transmissibility of 3.7 is measured at zero voltage in resonance frequency (10.5Hz). It is clearly observed that the displacement transmissibility is reduced in the neighborhood of the resonance frequency as the voltage is increased and finally 1.3 of transmissibility at 1kV. However, the performance exhibits bad results in the frequency range of 15-25Hz. This is because flow displacement is small in the high frequency, so there occurs weak stream ER fluid in squeeze flow not enough to overcome strong interaction force between particles in electric field. Also, there is no lock-up state in the squeeze mode ER mount which is major reason for the bad performance of vibration reduction in the flow mode ER mount.

Fig. 13 displays the measured and numerically simulated response of the displacement of mass when excited in the resonance frequency with constant voltage (0kV, 0.5kV, 1kV). Even though there are some differences in frequency range lower than resonance, mathematical model in Fig. 5 is found to be able to trace the responses of the squeeze mode ER mount with some accuracy.

Transmitted force of a mount is one of major factors to be considered in application, especially in navy ship. But it is difficult to investigate actually the transmitted force of a ER mount of 200kg static load for many reasons. In this paper, we use numerical simulations for the transmitted forces using mathematical model, equation (3) and (4). Simulated results of the transmitted force of the 200kg-squeeze mode ER mount with constant voltage are shown in Fig. 14. The data give us that the transmitted forces are increased as the input voltage increases in the frequency range upper than 15Hz. Therefore, an appropriate control scheme needs to be implemented to improve the performance in wide frequency range.

**IV.3 Performance Evaluation with Controller**

In this work, a skyhook controller which is known to be effective for a semi-active vibration control is adopted[10]. The control input which directly represents the controllable damping force is set by

\[
u(t) = c_{sy} \dot{x}(t) = F_{sy}(t)
\]

where \( c_{sy} \) is the constant gain. This implies physically the damping coefficients. The value of \( c_{sy} = 4000 \) is used in this paper. The damping force should be applied depending upon the relative motion to ensure the semi-active condition given by

\[
u(t) = \begin{cases} u(t) & \text{for } \dot{x}(t)(\dot{x}(t) - \dot{y}(t)) > 0 \\ 0 & \text{for } \dot{x}(t)(\dot{x}(t) - \dot{y}(t)) \leq 0 \end{cases}
\]

This condition physically indicates that the actuating of the controller 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 squeeze mode ER mount is
obtained by

\[ E(t) = \left[ \frac{3}{4} \left( \frac{h_0 + (x(t) - y(t))}{\pi R^3 \alpha} \right) u(t) \right]^{1/\beta} \tag{7} \]

or, input voltage is set to

\[ V(t) = \left[ \frac{3}{4} \left( \frac{h_0 + (x(t) - y(t))}{\pi R^3 \alpha} \right) u(t) \right]^{1/\beta} \cdot \left[ h_0 + (x(t) - y(t)) \right] \tag{8} \]

Fig. 15 shows measured displacement transmissibility with constant voltage including 0kV and skyhook controller. Simulated displacement result with skyhook controller is also appeared in Fig. 15. They indicate that controlled displacement transmissibility with skyhook algorithm becomes a little larger than that of constant voltage(1kV) below resonance frequency range, but good control result can be obtained above 15Hz. Also we can find good agreements between the controlled measured and simulation result in Fig. 15.

Fig. 16 presents numerical simulation results of the transmitted force of the ER mount in the case of uncontrol, constant voltage and control with skyhook controller. It is remarked that the uncontrolled response of the ER mount is obtained in the absence of the voltage. We see from Fig. 16 that the good control results in the transmitted forces can be derived by applying skyhook controller. We also see that there is some restriction of skyhook algorithm to control the transmitted force of the squeeze mode ER mount concurrently.

Controlled displacement transmissibility of the squeeze mode ER mount with skyhook algorithm, conventional rubber mount and flow mode ER mount are shown in Fig. 17 for the excitation of \( \pm 100\mu m \) amplitude[7]. We observe from Fig. 17 that controlled response of the proposed squeeze mode ER mount associated with skyhook controller shows better vibration isolation performance than conventional rubber mount and flow mode ER mount.

V. Conclusions

A squeeze mode electro-rheological(ER) mount, which can be adaptable to dynamic systems subjected to 200kg of static load, was proposed and its performance on vibration control was experimentally evaluated. It has been demonstrated that the displacement transmissibility can be substantially at the neighborhood of the resonance frequency by employing voltage control associated with the skyhook controller.

For the vibration reduction of small amplitude excitation in the higher frequency range, the proposed squeeze mode ER mount is found to be superior to the flow mode ER mount.

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. Since ER mount is to control unwanted vibration by supplying the damping force of ER mount to the dynamic system, transmitted force is also surely increased as the displacement performance increases. From this fact, it is necessary to use suitable control algorithm which can consider displacement(or velocity) and force simultaneously.

The potential applications of the proposed ER mount for vibration control include diesel engines, electric power supply units, and elastic decks of electronic and mechanical equipments.

References


Fig. 1 Schematic diagram of squeeze mode Bingham test apparatus

Fig. 2 Time response of damping force of ER fluid under squeeze mode motion (excitation: $\pm 20 \mu m$, 75Hz)

Fig. 3 Bingham Property of ER fluid under squeeze mode
Fig. 4. Configuration of the squeeze mode ER mount of 200kg static load

Fig. 5 Mathematical model of the squeeze mode ER mount

ER fluid properties $\alpha, \beta, \eta, E$
Electrode geometry $R, h_0$

Mount system parameter $Y_0, \lambda_{\text{in}}, \lambda_{\text{out}}$

$B_f(t) = f(\eta, R, h_0, x(t), y(t))$
$F_e(t) = f(\alpha, \beta, E, h_0, x(t), y(t))$

Mount system parameter $M, B_A, K_A$

Increment $f$

Solve dynamic equation

$$\dot{x}(t) + B_f(t)(\dot{x}(t) - \dot{y}(t)) + E_x(x(t) - y(t)) + F_e(t) = 0$$

Plot $X_0/Y_0$ v.s $f$

Fig. 6 Flow chart for the dynamic analysis of the squeeze mode ER mount
Fig. 7 Assembly of the squeeze mode ER mount

Fig. 8 Components of the squeeze mode ER mount

Fig. 9 Schematic diagram of experimental apparatus for ER mount
Fig. 10 Photograph of experimental apparatus for ER mount

Fig. 11 Measured force-displacement diagram for the 200kg squeeze mode ER mount at the resonant frequency(10.5Hz) with constant voltage

Fig. 12 Measured displacement transmissibility of the squeeze mode ER mount with constant voltage
Fig. 13 Comparison between measured and simulated results with constant voltage

Fig. 14 Simulated transmitted forces of the squeeze mode ER mount with constant voltage
Fig. 15 Comparison between measured and simulated results with constant voltage and skyhook controller

Fig. 16 Simulated results of transmitted forces of the squeeze mode ER mount with skyhook controller

Fig. 17 Measured displacement transmissibility of the squeeze mode ER mount of different operation modes with constant voltage and skyhook controller