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CONTROL OF STRUCTURES USING ELECTRORHEOLOGICAL DAMPERS

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ABSTRACT

The object this study is to demonstrate the use of electrorheological (ER) shear-wall dampers in a semi-active control system to attenuate seismically-induced structural motions. Material properties of ER suspensions (primarily the yield stress, and visco-elastic properties) increase by several orders of magnitude when subjected to strong electrical fields (kV/mm). Because viscous stresses are relatively un-affected by the field, it is desirable to design ER devices to operate at low shear rates. Damping walls are fluid-filled devices in which a thin layer of viscous or visco-elastic material is sheared between two large flat plates. These walls are well suited to ER materials, because of the low shear rates, small gap-size (3mm-5mm), and large surface area in these devices. Because the electric field controls yielding behavior of ER materials, ER devices are inherently non-linear. Non-linear control methods are required to derive control rules for ER devices. An approach based on Lyapunov's direct method results in a control rule for semi-active base isolation of seismically-excited structures. This control rule works equally well with structurally hysteretic structures and linear structures. Experimental evaluation of the ER control system shows that ER damping walls operated at zero voltage reduce structural vibrations considerably. Significant additional benefits are realized when the ER damping wall is operated according to the control rule.

KEYWORDS

Vibration control, Lyapunov stability, semi-active control, bang-bang control, control experiments, visco-elastic damper, friction damper, damping walls, electrostatic shielding.

INTRODUCTION

Motion suppression in civil engineering structures during strong earthquakes presents unique challenges for vibration control (Housner *et al.*, 1994). Properly detailed structures behave non-linearly during earthquakes, large control forces must be applied rapidly to respond to impulsive ground motions, but control forces need not be accurately controlled. The control system should be able to operate in the absence of external power.

ELECTRORHEOLOGICAL MATERIALS

Electrorheological (ER) materials have some unique properties that make them attractive candidates for use in semi-active earthquake protective systems. The mechanical properties (strength, stiffness and energy dissipation) of ER materials responds almost instantaneously (ms) to strong electric fields (kV/mm). The power required to produce the electric field is very small since advanced ER materials draw very little current (μAmps/cm^2) and have high dielectric strengths ($>$ 7 kV/mm). ER devices can regulate kN of force with only a few Watts of electrical power. Controllable devices using ER materials have few moving parts, and have good reliability with respect to mechanical failure. Electronic command signals are translated into modified device forces without the need for intermediate mechanical interfaces.

Modern intrinsic ER materials are suspensions of anhydrous, amorphous micron-sized particles, such as alumino-silicates, in a high-dielectric strength paraffin oil (Block and Kelly, 1988; Filisko and Radzilowski, 1990). When electrical fields are applied to these materials, electrostatic interactions between the particulates gives rise to the observed changes in mechanical properties. The modification in material properties is due, in part, to the fibration of particles between the electrodes. The source of the ER effect is not fully understood; suspensions with much improved ER activity (higher yield stress, faster response time, lower currents) could result from further materials science research (D.o.E., 1993).

Constitutive relations describing the behavior of ER fluids are strongly dependent upon applied external electric fields. The yield stress and visco-elastic properties in ER fluids change by orders of magnitude when strong electric fields are applied to them. Visco-elasticity is strongly affected by the field at low strains ($<$ 0.1); at high strains a yield stress is quadratically related to the field (Gamota, 1991). At large strains, and steady strain rates, $\dot{\gamma}$, the applied stress, τ, is resisted by a Newtonian component, $\eta\dot{\gamma}$, and a field-dependent yielding component, $\tau_{\rm y}(E)$.

$$\tau(E,\dot{\gamma}) = \tau_{\rm y}(E)\,{\rm sgn}\dot{\gamma} + \eta\dot{\gamma} \tag{1}$$

Material property response times due to increasing electric fields are governed by the finite device charging currents and the time for polarization and fibril formation. Discharge currents are much larger than charging currents, and close-range inter-particle repulsive forces disrupt the structure of fibrated particles within a few μs. So the response time for decreasing electric fields is governed largely by fluid inertia (Gavin, 1994). The maximum yield stress in current ER materials is on the order of 10 kPa. At high shear rates, the forces generated in ER devices are dominated by the (uncontrollable) viscous stresses. At low shear rates, ER devices provide a large range of controllable forces. Shear rates, and fluid inertia, become large in ER devices when fluid is forced to flow through the narrow laminar passageways at high volumetric flow rates. By contrast, the shear rates and inertia due to pure shear flow, such as in damping walls, are uniformly low.

ELECTRORHEOLOGICAL DAMPING WALL

Forces in dampers designed to use ER materials can be regulated by a factor of 1000 with response times of 1 to 10 ms (Gavin, 1994). Viscous damping walls can add very high levels of damping to structural systems (Arima *et al.*, 1988; Miyazaki *et al.*, 1992; Reinhorn, 1995). When filled with visco-elastic materials, these walls also add considerable stiffness to the structure, especially at higher frequencies. Damping walls reduce inter-story drift considerably but can increase the base shear. Damping walls filled will controllable materials, such as ER suspensions, can have adjustable levels of visco-elasticity. ER damping walls can provide the high levels of damping of passive damping walls, without the dramatic increase in base shear.

An ER damping wall consists of a metallic plate rigidly attached to a ceiling and submerged in a narrow metallic tank of ER material, which is rigidly connected to the adjacent floor. The gap between the plate and the tank is only a few millimeters. Assuming quasi-steady flow, homogeneous material properties, and ER behavior as given by (1), the force, F, generated by an ER shear wall can be simply approximated by $A\tau(E, \dot{\gamma})$, where A is the wetted surface of the suspended wall, and $\dot{\gamma}$ is the ratio of the damper velocity, v to the gap size, h.

The geometry of damping walls is well suited to ER fluid applications. The fluid gap is small enough to develop high electric fields; the large wetted area will develop large damping forces, despite the low yield stress; the low fluid shear rates result in a large range of controllable forces; the low fluid inertia results in fast response times; and the construction of the damping wall is simple.

NON-LINEAR CONTROL SYNTHESIS

A control synthesis, based on minimizing the kinetic energy content in a seismically-excited structure, leads to a bang-bang control rule, which is implemented with an analog feed-back loop. The equations of motion of a MDOF hysteretic structure subjected to earthquake accelerations, $\ddot{z}$, and incorporating N_D ER dampers (modeled by (1)) can be written:

$$M\ddot{x} + C\dot{x} + g(x) + A\sum_{i=1}^{N_D} b_i \tau_y(E_i)\mathrm{sgn}(b_i^T\dot{x}) = -M\ddot{z}, \tag{2}$$

where the N_D vectors b_i place the i^{th} ER damper force at the degrees of freedom between which the damper is attached. If the i^{th} ER damper is located between DOF's j and k, then the j^{th} element of b_i is 1 and the k^{th} element of b_i is -1. All other elements of b_i are zero. The term $g(x)$ is the gradient of the positive definite energy function, $W(x)$, describing the hysteretic behavior of the structural system. The maximum electric field which can be applied to the damper, $\bar{E}$, is limited by the dielectric break-down of the ER material. $(0 \leq E_i \leq \bar{E}, \forall i = 1, ..., N_D)$ The ER linear viscous forces $((A\eta/h)(b_i^T\dot{x}))$ are lumped into the structural damping matrix, C.

The kinetic plus potential energy of the structure is

$$V(x) = W(x) + \frac{1}{2}(\dot{x} + \dot{z})^T M(\dot{x} + \dot{z}). \tag{3}$$

Note that $V(x)$ is positive definite. The objective of the control is to minimize the rate of change of the internal energy in the structure, and thereby minimize the vibrational energy content as well (Buffinton, 1995). Differentiating (3) with respect to time, and inserting (2),

$$\dot{V}(x) = -\dot{x}^T C\dot{x} - \dot{z}^T(C\dot{x} + g(x)) - (\dot{x} + \dot{z})^T \sum_{i=1}^{N_D} b_i \tau_y(E_i)\mathrm{sgn}(b_i^T\dot{x}). \tag{4}$$

The last term of the equation is the only term influenced by E. The bang-bang control rule:

$$E_i = \begin{cases} \bar{E}_i & \text{if } b_i^T(\dot{x} + \dot{z})(b_i^T\dot{x}) > 0 \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

reduces $\dot{V}(x)$ to levels smaller than if the damper were operated at a constant field. Although this control rule is decentralized, it accounts for interactions between multiple ER dampers. The same control rule results for any monotonic relationship $\tau_y(E)$ and any function, $\tau_y(E, \dot{\gamma})$ that is odd in $\dot{\gamma}$

(McClamroch and Gavin, 1995). This control requires rapid on-off switching of the electric field when the ER device is installed as a base-isolation device, in the first story of a building, or between a bridge deck and abutment. For ER devices installed in any other location, the product on the r.h.s. of (5) is always positive. The control (5) is equivalent to a pseudo-skyhook friction damper (Karnopp *et al.*, 1974): the device force is out of phase with the absolute velocity of the 1^{st} degree of freedom, whenever possible. The control implementation requires sensing of relative velocity across the device terminals and the absolute velocity of one of the device terminals. The control is robust to scaling errors of the sensors, but is sensitive to bias and phase errors.

EXPERIMENTAL MODEL

Experiments on a small 3 DOF shear building model illustrate the effects of the control rule. The mass of each floor was approximately 1.25 kg and inter-story stiffnesses were 5.5 N/mm. The identified natural frequencies of the bare frame were 4.3, 12.7, and 18.8 Hz. The ER shear wall was constructed of stainless steel and poly-carbonate, and was installed between the first DOF and the ground, The ER material was 30% (v/v) anhydrous Zeolite "3A" in paraffin oil. The ER wall had a gap of 2 mm, and a wetted surface area, A, of 200 cm^2. The forces generated in the ER wall were on the order of the column shear. The ER device had a capacitance of approximately 10^{-10} F. To perform the required control tasks, the device was charged and discharged up to 100 times per second. Electrical transients are on the order of kilo-volts of potential, contained tenths of Amps of current, and lasted for only a few dozen micro-seconds. The electrical transients were attenuated by placing resistors in series with the ER device. Ten kΩ, 2 Watt carbon composition resistors worked satisfactorily in this regard. (On average, the ER device consumed less than one Watt of power.) Continuous, grounded, electrostatic shielding of all high-voltage components preserved the integrity of the low-level sensor signals.

The structure was excited on an electro-magnetic shaking table which made use of a proportional acceleration feedback control loop. This control was sufficient to obtain coherent transfer functions for the structure without the ER damper. Capacitive, dc-stable, silicon accelerometers measured absolute floor accelerations during the experiment. Figure 1 illustrates the structure with the ER wall, the sensors and the control circuit. All signals were low-pass filtered prior to digitization. Velocities were measured

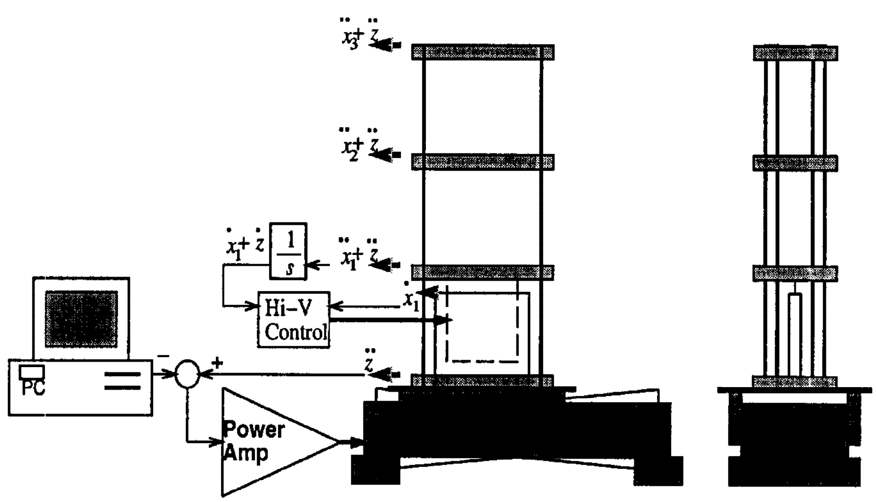

Fig. 1. Structural model illustrating shaking table system with feed-back control loops.

directly using self-generating inductive sensors. Because these sensors were self-generating, bias errors were minimal. The product on the r.h.s. of (5) was computed with an analog multiplier. A saturated op-amp took the sign of the product, which, in turn, controlled the solenoid of a tungsten-tipped, vacuum, high-voltage relay, through a transistor switch. The relay has a measured operate time of 2 ms, and connected the high voltage plate to the high-voltage supply $((\dot{x}_1 + \dot{z})(\dot{x}_1) > 0)$, or to ground $((\dot{x}_1 + \dot{z})(\dot{x}_1) < 0)$. High-voltage solid state can also perform this switching much more quickly (Tozer *et al.*, 1994), but are very expensive, and far exceed the response speed of the ER material itself. The high-voltage relay and power supply were shielded. Figure 2 illustrates the control circuit implementation.

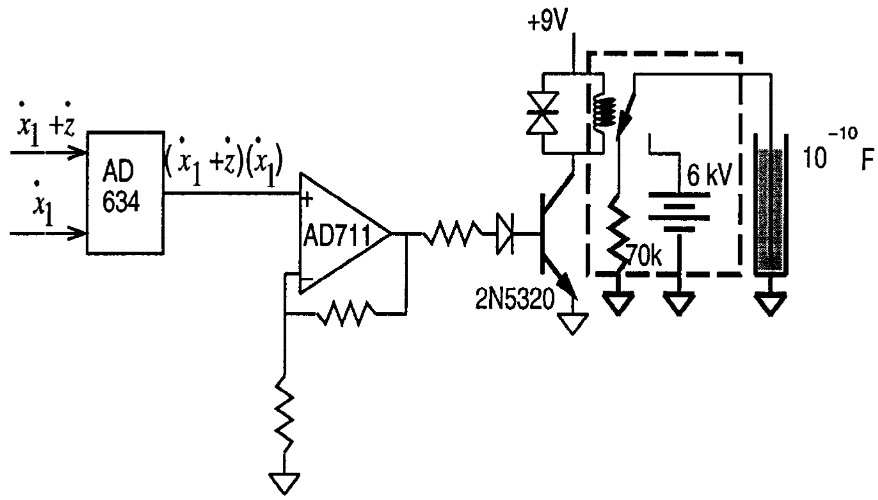

Fig. 2. Analog high-voltage control circuitry for carrying out the semi-active vibration control rule.

RESULTS

Four experimental cases are presented:

1. structure controlled using equation (5) (solid line in fig.'s 3, 4, and 5)
2. structure without ER damping wall (Bare Frame)
3. structure with ER damping wall at a constant 0 kV, and
4. structure with ER damping wall at a constant 6 kV.

In each of the experiments, the structures were subjected to wide-band ground accelerations for almost 1 minute. The ratios of spectral accelerations between the ground and each floor were then computed, as a measure of the performance of the controller. The frequency response functions were coherent up to about 15 Hz, and are shown in fig.'s 3, 4 and 5. Three well-separated peaks are evident for the bare frame structure in each figure. When the ER wall is operated at a constant 6 kV, the ER material deforms only slightly. The response spectrum of the first floor for this case is almost flat. All of the vibrational energy is put into the second and third DOF's, as evidenced by the high peak around 12 Hz in the second DOF. When the ER wall is operated at a constant 0 kV, large reductions in response are seen. The response reduction is further improved when the ER wall is operated according to (5), especially in the low frequencies.

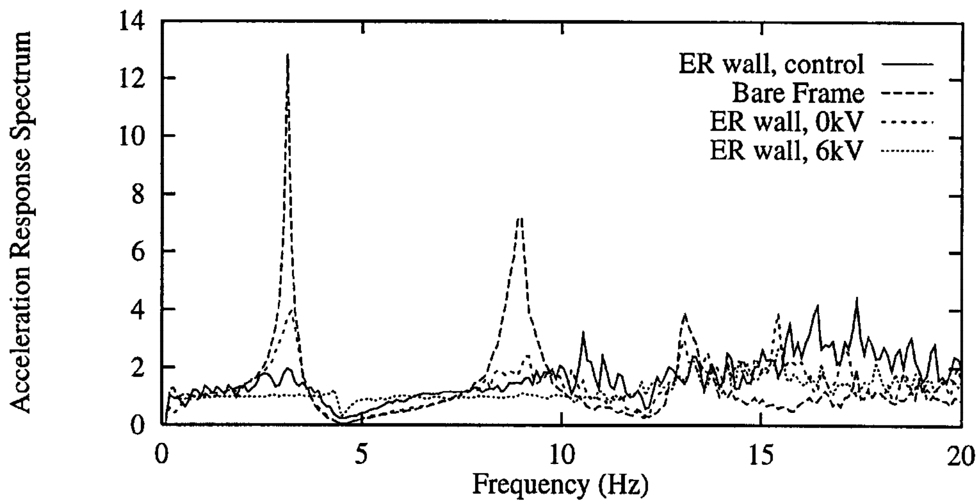

Fig. 3. Ratio of spectral accelerations between the ground and the first mass.

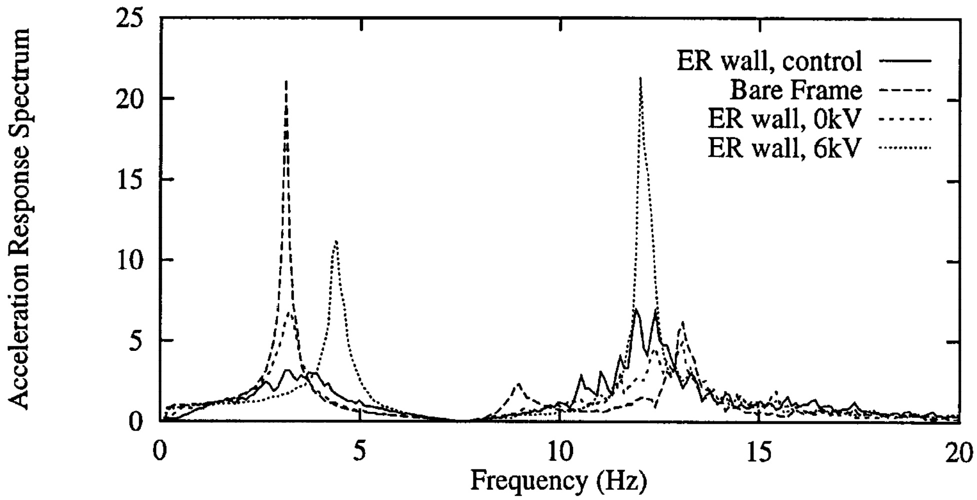

Fig. 4. Ratio of spectral accelerations between the ground and the second mass.

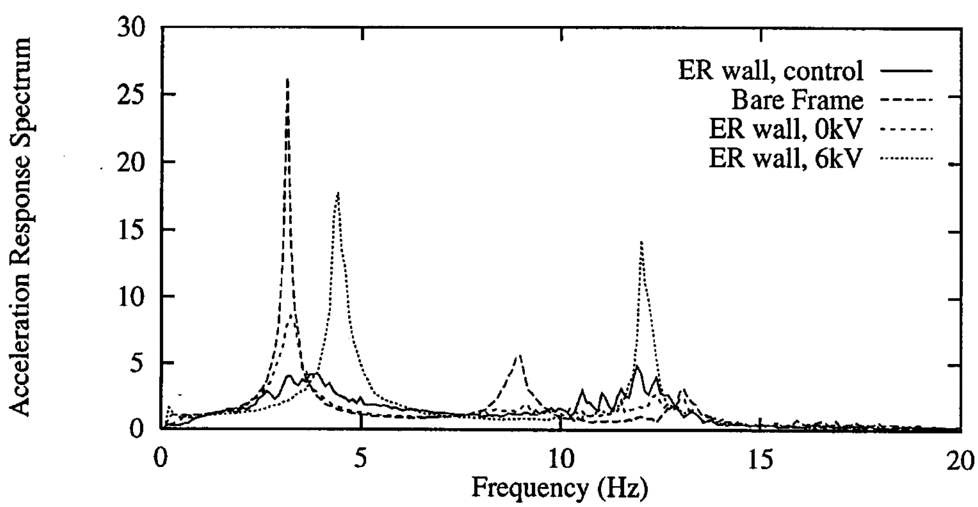

Fig. 5. Ratio of spectral accelerations between the ground and the third mass.

The goal of the control is to reduce the absolute kinetic energy of the structure. This velocity-based control rule suppresses accelerations at low frequencies better than high-frequency accelerations. A comparison of kinetic energies addresses the performance of the control rule directly. Absolute velocity time histories were computed from the measured displacements by filtering and integrating the time histories (Hamming, 1989). For each of the four cases, the average kinetic energy, $\overline{KE}$, was calculated

$$\overline{KE} = \frac{1}{2N} \sum_{k=1}^{N} \sum_{i=1}^{3} m_i(\dot{x}_i(t_k) + \dot{z}(t_k))^2 \tag{6}$$

The value of $\overline{KE}$ corresponding to case 1 was 15% lower than case 2, 25% lower than case 3, and 220% lower than case 4.

SUMMARY

This study concludes that ER dampers reduce structural motions, when operated in a zero voltage case. Additional improvements (on the order of 10% to 20%) are observed when the electric field is switched according to a bang-bang control rule which minimizes kinetic energy. Although operating the ER devices in a bang-bang fashion requires much more electrical energy than the constant voltage case, the control system can be operated using a battery-operated high-voltage supply. In the small scale experiments a single common 9V battery contains enough energy for hours of continuous operation. The control rule described here requires only that the structure is base-excited, that the function $\tau_y(E)$ is monotone and the force- velocity relationship for the ER damper is always in the first and third quadrants. At low strain rates, visco-elastic behavior of the ER device violates this last requirement. Because of the low, cyclic, shear rates of the material in these devices, pre-yield, visco-elastic behavior is observed in experiments. Designing the ER device to operate at higher shear rates would reduce the errors related to this assumption. The impulsive nature of the control forces may excite higher frequency modes, as is implied by fig.'s 3 and 4. This effect can be reduced by increasing the resistance in series with the ER device. So doing, the electrical time constant would lengthen, and force transients in the ER device would be longer.

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