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EXPERIMENTS WITH AN ELECTRO-RHEOLOGICAL FLUID TO CONTROL STRUCTURAL OSCILLATIONS

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ABSTRACT

Electro-rheological (ER) fluids can reversibly change from fluid to a solid-like gel when an electric potential is applied across them. An application of this characteristics is presented in this paper to provide variable damping for a tuned absorber. The variable damping tuned absorber is then used to control excessive oscillations of a resonant structure.

INTRODUCTION

Tuned vibration absorbers are simple and effective passive vibration control devices for lightly damped resonant structures. A simple system including a tuned absorber is shown in Figure 1(a). The structure to be controlled has a mass m_1, viscous damping coefficient c_1 and stiffness k_1, whereas m_2, c_2 and k_2 represent the corresponding parameters of the tuned absorber. Tuning is usually accomplished by $(k_1 / m_1)^{1/2} = (k_2 / m_2)^{1/2}$ where each side of the equality represents the undamped resonance frequency of the structure (ω_1) and the absorber alone (ω_2), respectively (Hunt 1979, Snowdon, 1968).

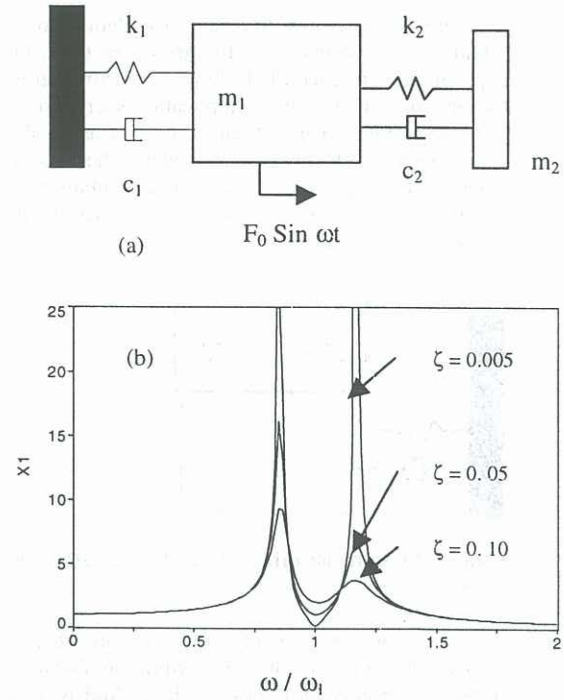


Figure 1 (a). A simple mechanical oscillator with a tuned absorber; (b) Response of the primary structure for different excitation frequencies.

In Figure 1(b), the displacement amplitude of the undamped ($c_1 = 0$) structure, X1, is shown for different frequencies of the excitation $F_0 \sin\omega t$. Representative results in Figure 1(b) are for $m_2/m_1 = 0.10$ and for three different damping ratios of the absorber of $\zeta = 0.005$; 0.05 and 0.10 ($\zeta = c_2/2(k_2 m_2)^{1/2}$)

The best control is obtained at $\omega = \omega_1$ and for $\zeta = 0.005$ Hence, when the structure to be controlled is excited at the tuning frequency, an almost perfect control effect can be obtained with a virtually undamped absorber. This tuning frequency may be very important practically if the structure to be controlled is a machine which is to operate at this particular tuning frequency. The problem, however, is that the addition of the undamped absorber introduces a resonance of the combined system at a frequency lower than the tuning frequency. As the machine is started from rest, before the steady operating speed is reached, this resonance has to be traversed in transient. If not controlled effectively, such transient resonances could cause significant damage.

Passing through the transient resonance quickly would certainly alleviate the problem, but at the expense of providing an over-designed driver. Since the driver would not normally need this power, accelerating through the resonance frequency quickly forces the design to be wasteful. An effective vibration controller, therefore, is very desirable to avoid wasteful design.

Including some damping in the tuned absorber reduces the adverse effects of the transient resonance significantly as shown with the two additional cases for ζ of 0.05 and 0.10 in Figure 1(b). The problem this time, however, is that the tuning effect is lost as the resonance amplitudes are reduced to acceptably low values. At the steady operating frequency ($\omega = \omega_1$), a damped tuned absorber is worse off than the undamped one depending upon the level of damping in it.

An ideal absorber would be the one which would have the characteristics of a damped tuned absorber as the first resonance is traversed, but switch to an undamped one, once the steady state frequency is reached. A sloshing absorber is suggested here to perform this dual function.

SLOSHING ABSORBER WITH AN ELECTRO-RHEOLOGICAL FLUID

Sloshing refers to low frequency oscillations of a liquid in a container. In most engineering applications, presence of sloshing is detrimental to the integrity of the related application such as that in transportation of liquid cargo. In contrast to the suppression of sloshing, the objective here is to employ sloshing of a liquid in a container to dissipate oscillatory energy of a structure as suggested in Figure 2.

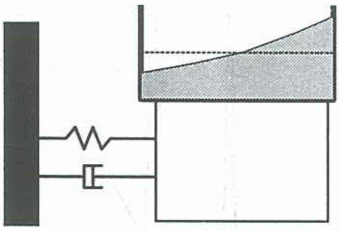


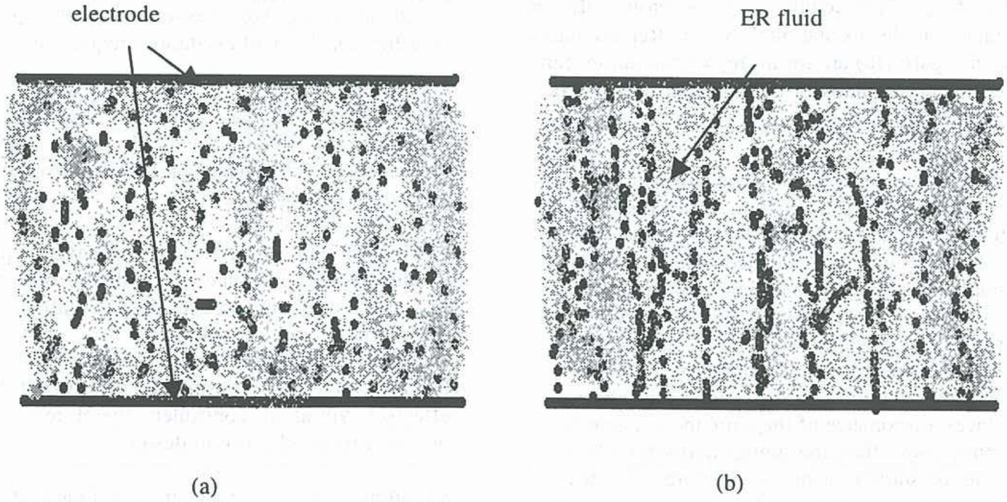
Figure 2.Sloshing absorber attached on the structure to be controlled.

The operation principal of a sloshing absorber is very similar to that of the tuned vibration absorber. Instead of another oscillator, sloshing fluid is used to provide the required force opposition to achieve the control. The control force is the pressure force applied on the side of the container of the sloshing fluid. Earlier work suggested promising designs for an effective sloshing absorber (Anderson et al. 1998). An electrorhelogical fluid will be used here as a working liquid of the sloshing absorber.

Electro-rheology (ER) is the phenomenon in which the rheology of the fluid is modified by the imposition of electric fields. It has been discovered that the viscosity of an ER fluid increases with the increasing electrical field applied on it (Guozhi et al. 1995; Choi and Park, 1994). ER fluids are Newtonian in the absence of an electric field. However, as suggested in Figure 3, when the electric field is raised to a high enough strength (in the order of several kVolts over distances of a few mm), ER fluid starts to assume the character of a solid and can be subjected to shear stresses. One of the most useful properties of the ER fluid is that the phase change takes place over milliseconds, and it is completely reversible.

What is proposed in this paper is to use an ER fluid as the working fluid of a sloshing oscillator. Such an indirect application of the ER fluid will be to have a liquid which is free to slosh when there is no voltage. By selecting its parameters appropriately (Anderson et al.), this sloshing ER fluid absorber could be quite effective as an energy dissipator. Once the voltage is applied to transform the phase of the ER fluid, dissipative effect is replaced by simply an added mass effect of the solid-like ER fluid.

The two very different energy dissipation trends discussed above, could therefore be used as a variable damping source for the tuned vibration absorber. As the structure builds its speed up to the steady speed in relation to Figure 1 (b), no voltage is required to obtain high damping in the absorber. Once the steady operating speed is reached, the damping in the absorber could be "switched off" by solidifying the working fluid to obtain minimal oscillation amplitudes at the operating speed.



(a) (b)

Figure 3. Schematic representation of the ER fluid (a) without the electric field and with dispersed particles, and (b) with the electric field and with polarised particles.

EXPERIMENTS

Figure 4 shows the experimental setup used to implement the suggested ER fluid sloshing absorber as the variable damping of a tuned absorber. In this figure, the structure to be controlled is a rigid mass mounted on four thin aluminium strips from a fixed base. The tuned absorber is another similar oscillator mounted on the mass of the first structure. The tuned absorber also accommodates the container of the sloshing absorber. The width of a square plastic food container of 100 mm, is divided into 5 equal compartments with aluminium electrodes. Hence, each compartment had the length of 100 mm in the direction of sloshing. Light density paraffin oil with corn starch (of 40% volume fraction) is used as the ER fluid. The depth of approximately 25 mm fluid produces a fundamental sloshing frequency of 2.7 Hz. The system parameters are summarised in Table 1. Of importance in this table, are the two critical damping ratios reported for the tuned absorber. The damping ratio is 0.007 when the ER fluid is solidified, and 0.050 when it is allowed to slosh.

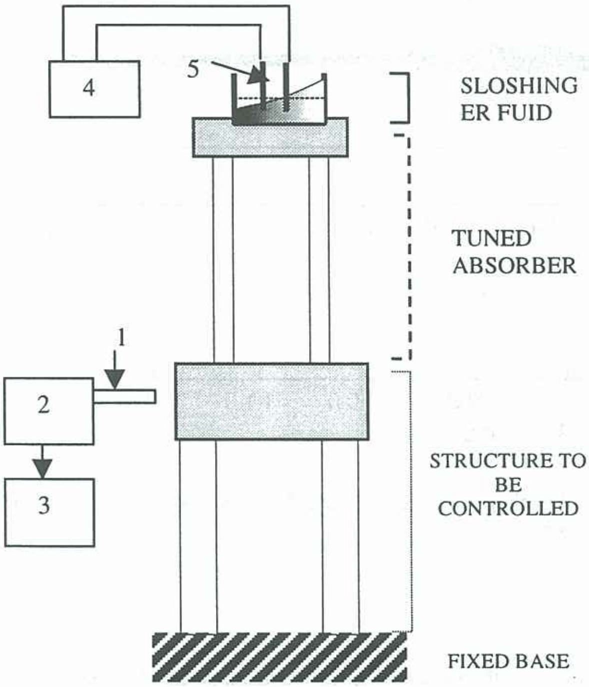


Figure 4. Schematic of the experimental setup
1: KEYENCE LB-12 Laser transducer; 2 : KEYENCE LB - 72 Amplifier; 3 : Personal computer and data acquisition; 4: FLUKE 408B High voltage source; 5: Electrodes (0.5mm thick aluminium).

Experimental procedure consisted of mounting an electric motor with a rotating unbalance on the structure whose speed of rotation changed linearly from zero to 2.7 Hz in 100 seconds. Then the speed was kept at this tuning frequency to observe the steady state response for 40 seconds. This electric motor is not shown in Figure 4. The response of the structure was measured with a non-contact transducer (1 and 2 in the figure) and stored in a personal computer for processing Voltage to the sloshing liquid was provided by a high voltage source (4) which was connected to the six electrodes in the plastic container. Only two electrodes are shown in the figure for clarity.

RESULTS

Displacement history of the structure is shown in Figures 5(a) and 5(b) for the cases when the full voltage and no voltage was applied, respectively. This full voltage resulted in a potential of 0.25 kV/mm between the electrodes which was enough to solidify the ER fluid. The third frame corresponds to the controlled case where the ER fluid was free to slosh until 100 seconds. After the steady state was reached at 100 seconds, full voltage was applied to prevent sloshing. In these frames, first 30 seconds of data was skipped as no significant oscillations could be observed at these low frequencies. Any time after 100 seconds, corresponds to the constant speed of the rotating unbalance.

Full voltage case in Figure 5(a) displays the characteristic trends of a lightly damped tuned absorber. The transient resonance effect is very clear as the first resonance frequency is traversed around 85 seconds with a peak-to-peak response of approximately 10 mm. As a result of minimal structural damping, the peak-to-peak displacement amplitude at the tuning frequency is approximately 0.4 mm. In Figure 5(b), no voltage case, the ER fluid is allowed to slosh and provide damping for the tuned absorber. As a result of this damping, the peak-to-peak displacement is only 2.85 mm which is approximately three times smaller than that in Figure 5(a). However, the response at the tuning frequency is as large as 1 mm, about 2.5 times larger than that of the full voltage case. The variable voltage case in Figure 5(c), successfully combines the small transient of the large damping case and the small steady state of the small damping case.

CONCLUSIONS

ER fluids have the unique capability of switching between a Newtonian fluid and a solid-like gel when an electric potential is applied on them. An experimental investigation is presented in this paper to use an ER fluid as a means to provide variable damping to control excessive oscillations of a resonant structure. Results seem promising. These results are a part of an ongoing investigation.

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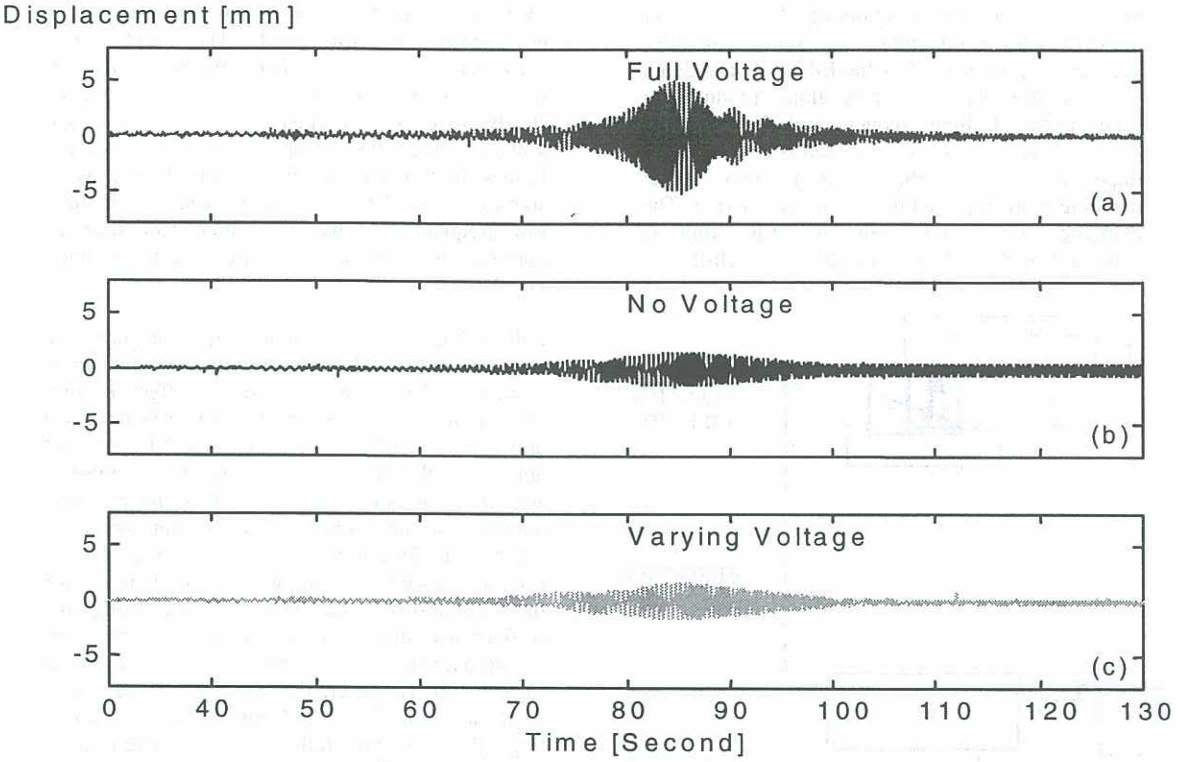

Figure 5. Displacement history of the structure for (a)full voltage of 0.25 kV/mm, (b) no voltage and (c) the variable voltage case where the full voltage was applied at 100 seconds.

Table 1. Structural parameters of the experimental setup. ζ refers to the values when each system is tested alone.

	Fundamental freq. (± 0.1 Hz)	Mass, (kg)	Equivalent damping ratio, ζ (± 0.005)
Primary structure	3.0	4.0 ± 0.1	0.006
Sloshing container	2.7	0.236 ± 0.001	-
Absorber with sloshing container	2.7	1.1 ± 0.1	0.007 (at 0.25 kV/ mm) 0.050 (at 0 kV/ mm)