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PERFORMANCE CHARACTERISTICS OF A VIBRATION ISOLATOR WITH ELECTRO-RHEOLOGICAL FLUIDS

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The conflicting requirements on the damping capacity of a vibration isolator in the low-and high-frequency regimes can be achieved by actively controlling a damper with electro-rheological fluid. Experimentally obtained results on two colloidal suspensions, one based on silica powder and the other on starch powder, are reported. While both demonstrate considerable reduction in the near-resonance transmissibility, the starch based fluid exhibits Coulomb damping characteristics at a high field strength. This, in turn, restricts the transmissibility to less than or equal to unity at all frequencies even when the isolator is used in a passive manner.

1. INTRODUCTION

Insertion of resilient elements between the source and receiver of vibration is an extremely popular method of vibration control. The system, comprising these elements, as a whole is called a vibration isolator. A common construction of a vibration isolator consists of a helical spring in parallel combination with a viscous damper. The effectiveness of such an isolator, during the steady-state operation under harmonic excitation, requires high damping capacity (viscosity) if the excitation frequency is low (less than $\sqrt{2}$ times the natural frequency). However, in the normal operating range, with the excitation frequency greater than $\sqrt{2}$ times the natural frequency, high damping capacity is detrimental to the performance of an isolator [1]. These conflicting requirements on the damping capacity very often necessitate compromise solutions as achieved by using mechanical stops (to cross through resonance) or parallel anti-vibration rubber mounts with frequency-dependent characteristics [2]. Thus, for a broadband excitation

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(especially with starting and stopping phases), normally an actively controlled damper is more suitable then a passive one [3].

An actively controlled damper can be constructed by incorporating an electro-rheological (ER) fluid to provide the viscous resistance. An electro-rheological fluid is a colloidal suspension, the viscosity of which changes by several orders of magnitude on the application of an electric field [4]. A number of mechanical devices like valves, clutches, dampers, etc. have been fabricated by utilizing this property of electro-rheology, also known as the Winslow effect [5–7]. The electrical, rheological and mechanical properties of ER fluids have also been reported by several researchers [8–10].

In this paper, the construction and performance characteristics of a vibration isolator, consisting of a parallel combination of a helical spring and a piston-cylinder dashpot with ER fluids, are discussed. Experimentally obtained results are reported for two different fluids, one of which is silica-based (SIB) and the other starch-based (STB). The effects of various parameters like the particle concentration (% w/w), the nature (AC or DC) and strength of the electric field, the shear-rate etc. are discussed. It has been found that with the STB fluid, it is possible to reach a phase where the damper exhibits Coulomb damping characteristics. Consequently, the harmonic transmissibility could be restricted to less than or equal to unity at all excitation frequencies.

2. EXPERIMENTAL DETAILS

2.1. EXPERIMENTAL SET-UP AND METHOD

The experimental set-up is aimed at constructing a single-degree-of-freedom vibrating system (Figure 1) consisting of a rigid mass connected to a harmonically oscillating base (the shaker table) through a helical spring and a piston-cylinder dashpot. The table movement is given by $y = Y \cos \omega t$, where the amplitude Y and the excitation frequency ω can be varied independently and held constant. The steady-state response of the mass can be written as $x = X \cos(\omega t - \varphi)$. The effectiveness of the isolator is measured in terms of harmonic transmissibility (an inverse index) $T = X/Y$. A sectional view of the assembly is shown in Figure 2. The guiding cylinder (of mild steel) ensures movement of the system in the vertical direction. The Teflon cover minimizes friction and prevents a short circuit. Figures 3 and 4 show the photographs of the various components and the assembled configuration, respectively. The cup-shaped piston and the dashpot cylinder are made of commercial grade copper. The top end of the piston rod and the dashpot cylinder are connected to two terminals of an electrical power source. Rigid blocks of different sizes were attached to the cover of the guiding cylinder (loading platform) to control the mass of the vibrating system. The stiffness of the spring, measured by a universal testing machine, was 11·11 N/mm. The dimensions and other minor details of the set-up are available in reference [11].

The dashpot cylinder was fixed on to a mild-steel base plate which, in turn, was mounted on a vertically oscillating shaker table (Make: All American Tool & Manufacturing Co., Skokie, IL, U.S.A.). The amplitude and frequency of

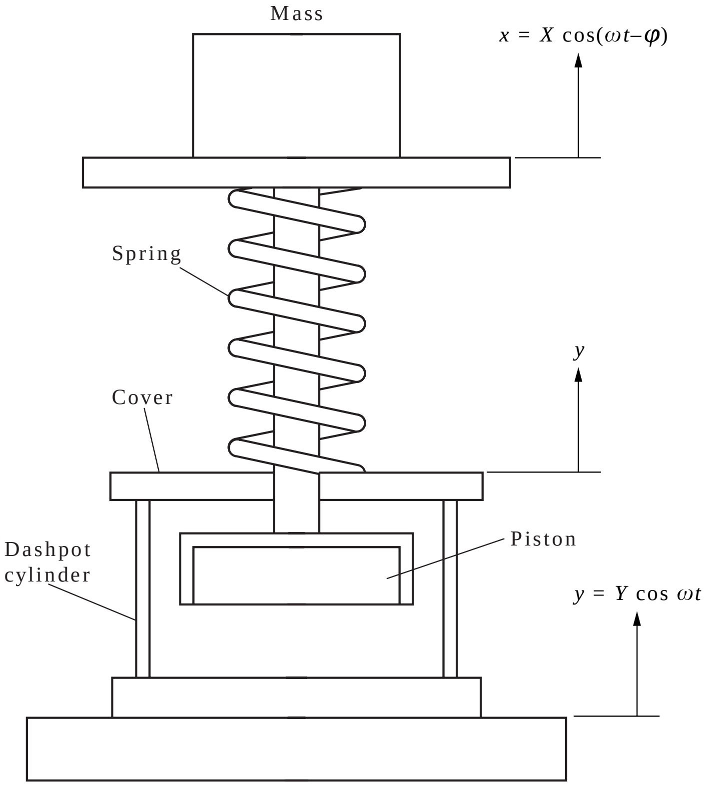

Figure 1. Vibration isolator with base excitation.

oscillation of the table can be set within ranges 0–1·9 mm (0–0·075 in) and 5–100 Hz, respectively. The vibratory displacements (amplitudes) X and Y are measured by using B&K accelerometers (4370) and charge amplifiers (4365). The transmissibility values ($T = X/Y$) were obtained over a narrow range of frequency covering the resonance zone. The frequency of excitation was increased and decreased with a step size of 1 Hz and the readings were recorded after attaining the steady state. The signals from the charge amplifiers were also fed to a dual beam, digital storage oscilloscope (Kikusui make) to observe the waveforms of the vibratory displacements.

Both AC and DC power sources were used to provide the electric field between the piston and the dashpot cylinder having a radial clearance of 0·8 mm. The DC supply had a rating of maximum 3 kV and 30 mA, whereas the AC supply had a rating of maximum 5 kV and 45 mA.

2.2. PREPARATION OF ER FLUIDS

As already stated, two different ER fluids were prepared. For the SIB fluid, coarse silica was ground by planetary milling after adding a little water. This finely powdered, semi-solid mass was then heated in an oven at 70°C for 12–14 h. Care was taken to dry the powder without sintering it. The dried mass was again milled (dry) to produce a homogenous fine powder. The shape and size of the particles

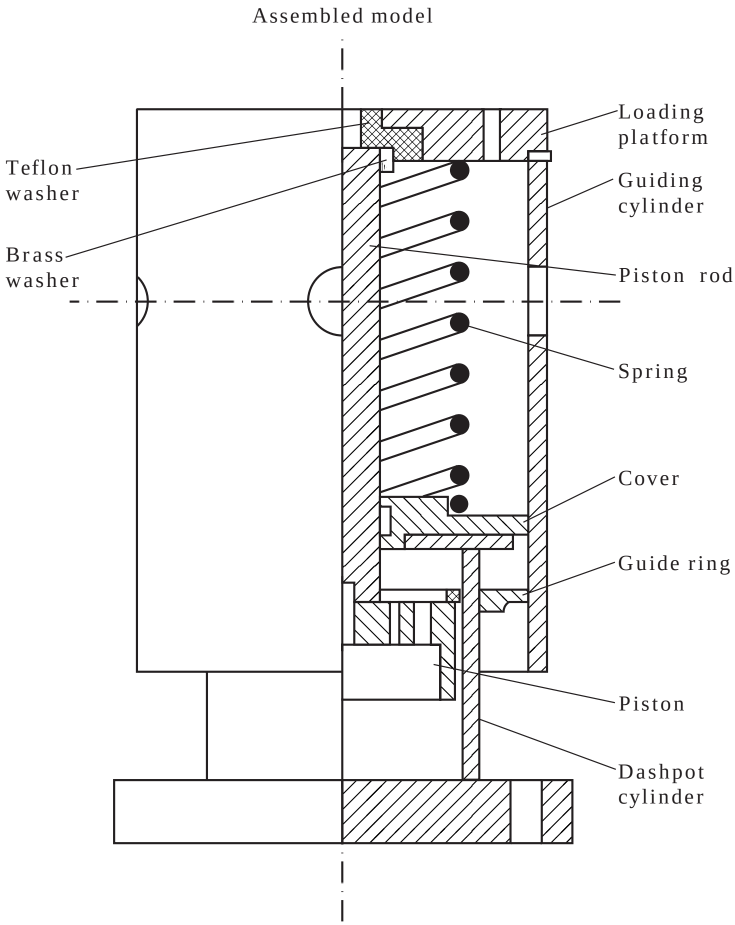

Figure 2. Sectional view of the assembled set-up.

were analyzed through an electron microscope. It was observed that the particles were irregular in shape with sizes ranging between 1 and 5 μm.

Xylene was used as the dispersing phase, to which triple distilled water and glycerol mono oleate (as surfactant) were added. This solution was continuously stirred as silica powder was gradually added. This resulted in a semi-solid paste which, after undergoing continuous shearing in the dashpot cylinder, ultimately turned into a homogeneous colloidal suspension having good flowability. Only after reaching this liquid state, the ER effect was demonstrated. The ohmic resistance of the fluid in the electrode gap was around 200 kΩ. Two fluids with silica contents 36% (w/w) and 42% (w/w), respectively, were prepared. In both these mixtures, water and surfactant content was 5.5% (w/w) each.

For the preparation of the STB fluid, first kitchen flour was ground dry by planetary milling. The particles were found to be almost spherical in shape with sizes ranging between 15 and 25 μm. The ground starch was added to a mixture of xylene and a small amount of water. The mixture was continuously stirred and the surfactant (glycerol mono oleate) was gradually added. Two fluids with starch

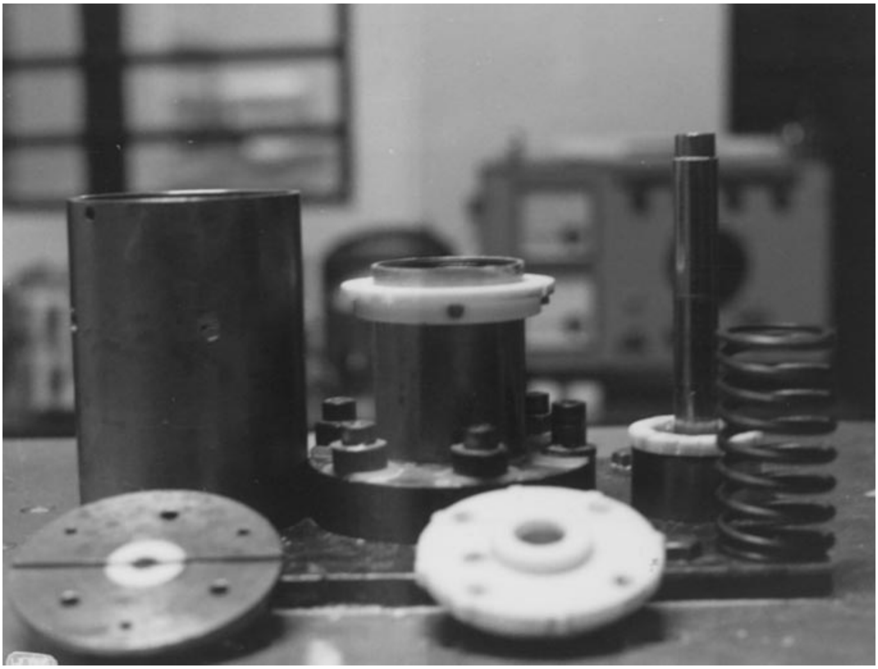

Figure 3. Various components of the spring-damper assembly.

contents 40% (w/w) and 55% (w/w), respectively, were prepared. In both these suspensions, water and surfactant content was 4% (w/w) each. Unlike the SIB fluids, the STB fluids were found to be readily usable as soon as these were prepared. The ohmic resistance of the electrode gap with these fluids was found to be 400 kΩ.

3. RESULTS AND DISCUSSION

The SIB fluids were tested with a DC field. Figures 5 and 6 show the variation of the transmissibility (T) with excitation frequency (ω) at different field-strengths (E) for two different silica-particle concentrations. The field strength was increased until the power supply tripped. The field-strength was assumed to be uniform within the electrode gap. In these figures, the theoretical transmissibility values for an undamped isolator are indicated by the dashed curve. Also the experimentally obtained near-resonance transmissibility values (for a specific field strength) are joined by smooth curves. It is clearly seen that the electroviscosity of the fluid increases with increasing field-strength which, in turn, reduces the near-resonance transmissibility. However, this effect tends to saturate at high field-strengths. Comparing the reduction of the maximum transmissibility values (from zero to some given field strength) depicted in Figures 5 and 6, it can be concluded that the electroviscosity increases as the particle-concentration increases from 36 to 42% (w/w). This is due to the availability of more ions with higher concentration of particles. A small amount of current was seen to flow at the onset of the ER effect. However, the maximum field-strength that could be attained without

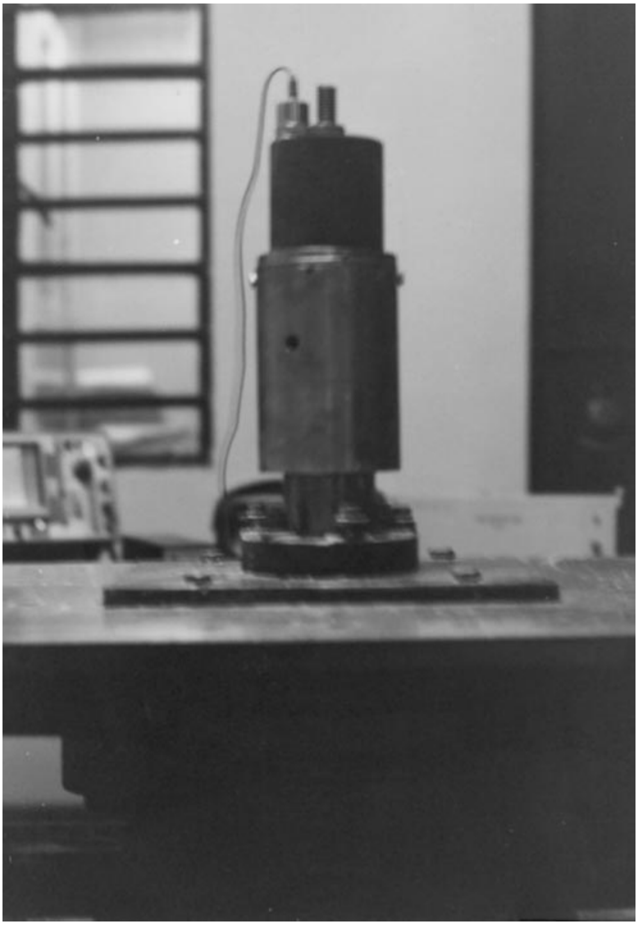

Figure 4. Assembled set-up on the shaker table.

tripping the power supply (i.e., reaching its maximum current rating) was less with higher concentration of the particles. Experiments were conducted by switching the electric field on and off. It was observed that the onset of electroviscosity is instantaneous with the application of the electric field. But on removing the field, the disappearance of the electroviscosity was somewhat gradual.

By reducing the mass on the loading platform, the resonance frequency was increased (to around 12 Hz from around 8 Hz, as shown in Figures 5 and 6). This, in turn, changed the shear rate. The maximum shear-rate at resonance is approximately given by $\omega_n(A_m^2 + A_b^2)^{1/2}/d$, where ω_n is the natural frequency, d is the electrode gap and A_m and A_b are the steady state displacement amplitudes of the mass and the base (shaker table), respectively. The transmissibility plots with this increased frequency and 42% silica concentration are shown in Figure 7. The maximum shear rates corresponding to Figures 6 and 7 (at zero field strength) are obtained as 550 and 810 rad/s, respectively. As expected [9], it is noted from these figures that with lower shear-rate, the electroviscosity (revealed by the reduction

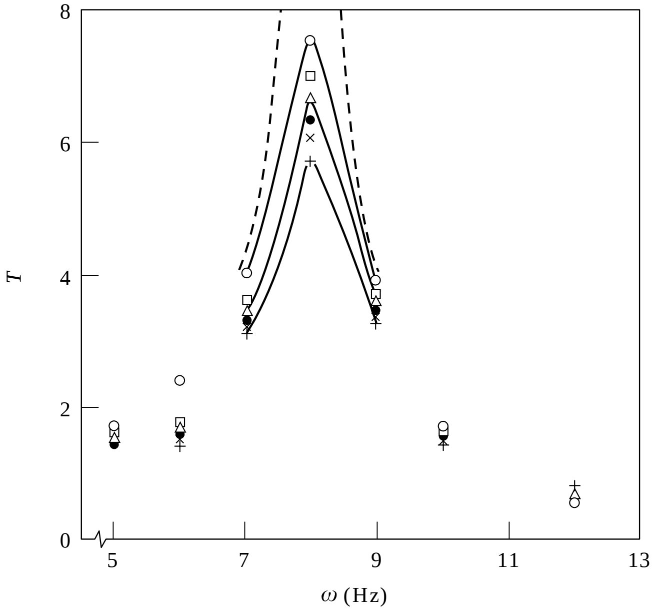

Figure 5. Transmissibility with SIB fluid having 36% silica at various field strengths (E in V/mm): ○ (0), □ (625), △ (875), ● (1250), × (1500), + (1875); ––– undamped (theoretical).

factor of near resonance transmissibility at the same field strength) is more pronounced.

Two STB fluids were tested with the application of an AC field (50 Hz). Results are reported here for a system with a resonance frequency around 7 Hz. Figures 8

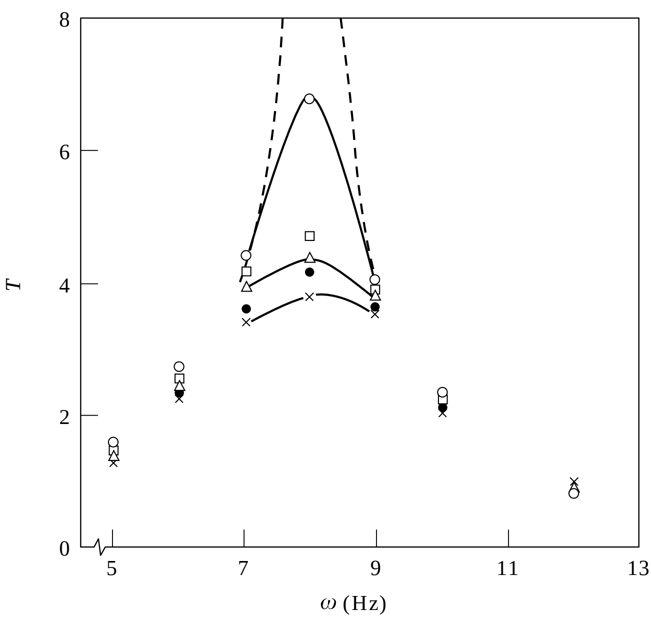

Figure 6. Transmissibility with SIB fluid having 42% silica at various field strengths (E in V/mm): ○ (0), □ (625), △ (875), ● (1250), × (1500); ––– undamped (theoretical).

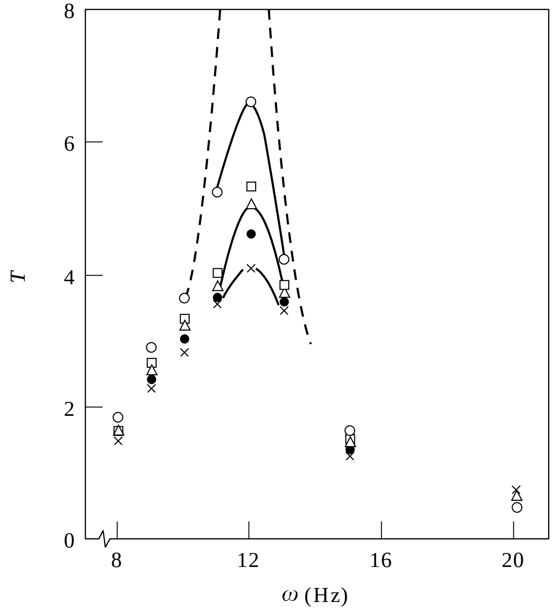

Figure 7. Transmissibility with SIB fluid having 42% silica at various field strengths (E in V/mm): ○ (0), □ (625), △ (875), ● (1250), × (1500); ––– undamped (theoretical).

and 9 show the transmissibility plots with the STB fluids. In Figure 9, the horizontal line denotes unit transmissibility. With 40% starch concentration, a field higher than 1500 V/mm tripped the power supply. However, with a higher starch concentration (55%), a still higher field (=2375 V/mm) could be applied.

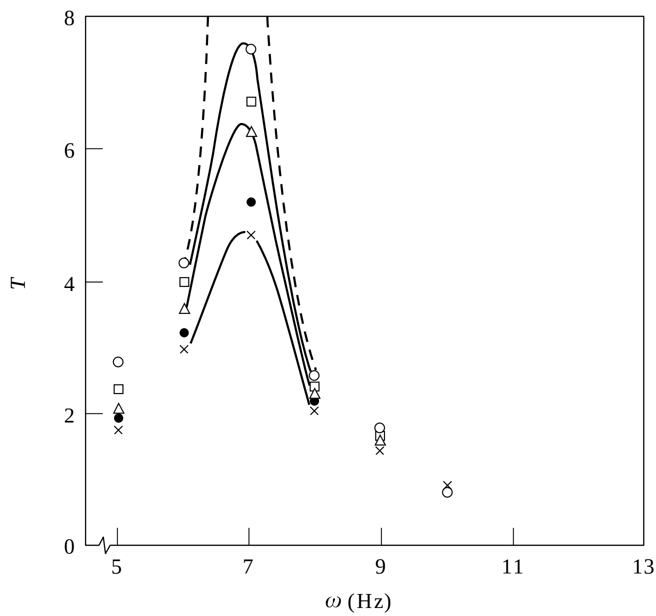

Figure 8. Transmissibility with STB fluid having 40% starch at various field strengths (E in V/mm): ○ (0), □ (625), △ (1000), ● (1250), × (1500); ––– undamped (theoretical).

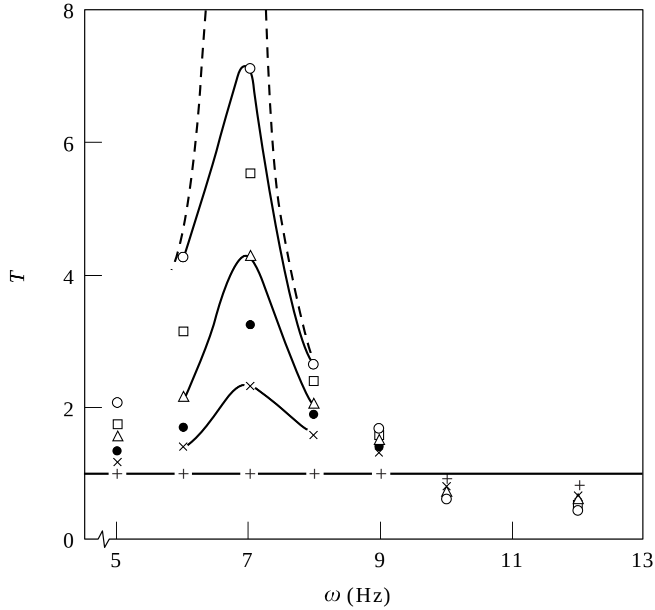

Figure 9. Transmissibility with STB fluid having 55% starch at various field strengths (E in V/mm): ○ (0), □ (625), △ (1000), ● (1250), × (1500), + (2375); --- undamped (theoretical).

Note that in the case of SIB fluids with a DC field, the maximum applicable field strength was reduced with increasing particle concentration.

It is obvious from Figure 9 that with 55% starch concentration, the ER damper behaves like a Coulomb damper when the field strength is 2375 V/mm. Consequently, the transmissibility could be maintained at unity up to the break-loose frequency [2]. Until this frequency is reached, the isolated mass and the base move as one rigid body and no slip occurs at the damper. In other words, the limiting or the maximum Coulomb friction force remains greater than the maximum inertia force of the isolated mass. If the break-loose frequency is increased beyond $\sqrt{2}\omega_n$, then the transmissibility can be maintained at $\leqslant 1$ (see Figure 9). When this critical condition of Coulomb damping is reached, the system ceases to behave linearly. As a consequence, the waveform of the displacement of the top mass was seen to be distinctly distorted relative to that of a sine wave [11].

In STB fluids, unlike in the SIB fluids, both the appearance and disappearance of the ER effect were observed to be instantaneous with the application and removal, respectively, of the electric field. The onset of ER effect was exhibited without any flow of current. A current started flowing only after reaching a critical field-strength. The value of this critical strength increased with higher particle concentration. Once the field-strength exceeded the critical value, the current increased rather sharply [11]. It was also observed that at a slightly higher temperature (around 50°C), the performance of the STB fluid deteriorated whereas that of the SIB fluid was not much affected. Furthermore, the dispersing phase xylene, being volatile, needed replenishment. Finally, silicon powder being abrasive, the SIB fluids were damaging the Teflon washers.

For optimum performance over a wide range of frequency, the vibration isolator discussed in this paper should be used in an active manner. Either the amplitude of the isolated mass or the frequency of excitation should be sensed and used to switch on or off the electric field.

4. CONCLUSIONS

A single-degree-of-freedom vibration isolator can be fabricated using electro-rheological fluids as the damping medium. Experiments have shown that the electro-viscosity of two fluids gives rise to considerable reduction in the near-resonance transmissibility. A starch-based fluid exhibited Coulomb damping characteristics at a high field strength. Using this fluid even in a passive manner (with the field always on), the transmissibility can be maintained at less than or equal to unity at all frequencies. For optimum performance, such an isolator should be actively controlled.

REFERENCES

1. J. C. SNOWDON 1968 *Vibration and Shock in Damped Mechanical Systems*. New York: Wiley.
2. A. K. MALLIK 1990 *Principles of Vibration Control*. New Delhi: Affiliated East–West Press.
3. J. C. SNOWDON 1970 *The Shock and Vibration Bulletin* **41**, 21–60. Isolation from mechanical shock with a mounting system having nonlinear dual–phase damping.
4. H. BLOCK and J. P. KELLY 1988 *Journal of Physics* (*D*) **21**, 1661–1677. Review article: electro-rheology.
5. T. G. DUCLOS 1988 *Automotive Engineering* **96**, 45–48. Electro-rheological fluids and devices.
6. M. J. BRENNAN, M. J. DAY and R. J. RANDALL 1995 *Smart Material Structure* **4**, 83–92. An electrorheological fluid vibration damper.
7. W. M. WINSLOW 1962 *US Patent Specification* 3, 047,507.
8. D. L. KLASS and T. W. MARTINEK 1967 *Journal of Applied Physics* **38**, 75–80. Electroviscous fluids II—electrical properties.
9. D. L. KLASS and T. W. MARTINEK 1967 *Journal of Applied Physics* **38**, 67–74. Electroviscous fluids I—rheological properties.
10. N. G. STEVENS, J. L. SPORSTON and R. STANWAY 1987 *Transactions of the American Society of Mechanical Engineers*, *Journal of Applied Mechanics* **54**, 456–458. On the mechanical properties of electro-rheological fluids.
11. I. TANDON 1997 *M.Tech Dissertation*, *I.I.T. Kanpur*. Design, fabrication and testing of an electro-rheological fluid damper.