Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Sound and Vibration 264 (2003) 235–244
JOURNAL OF SOUND AND VIBRATION
www.elsevier.com/locate/jsvi

Letter to the Editor

Experiments for control of structural oscillations using free and restricted sloshing waves

Tam D. Troung, S. Eren Semercigil*, Özden F. Turan

Faculty of Engineering and Science, School of the Built Environment—Mechanical Engineering, Victoria University of Technology, P.O. Box 14428, Melbourne, Vic. 8001, Australia

Received 15 April 2002; accepted 11 November 2002

1. Introduction

Sloshing is low frequency oscillation of a liquid in a partially full container. The concept of using intentionally induced sloshing for structural control was suggested earlier by Fuji et al. [1], Abe et al. [2], Kaneko and Yoshida [3] and Seto and Modi [4]. These works mostly dealt with travelling sloshing waves which result from shallow liquid levels. Travelling waves are preferable to standing waves because of their good energy dissipation characteristics. Standing sloshing waves, on the other hand, are poor energy dissipators [3,5]. Generally, standing waves result from having liquid depths comparable to the length of the container. Deep liquid levels are important practically as they occur in storage containers. It would be desirable to use these storage containers as structural controllers since they may already exist as part of the structure to be controlled.

A simple mechanical oscillator with a sloshing absorber (represented by the container having a free liquid surface) is shown in Fig. 1. For a sloshing absorber, the liquid container is designed such that there is strong interaction between the sloshing liquid and the oscillator. However, even with strong interaction, a standing-wave-type sloshing absorber has poor energy dissipation [5]. In this study, a cap is placed above the free surface to partially restrain the surface wave to enhance the energy dissipation capability of a standing sloshing wave. The expectation here is to dissipate energy through plastic impacts of the rising wave with the cap. The suggested configuration is illustrated in Fig. 2(a).

In Fig. 2(b), an impact damper is shown which employs a principal of operation similar to that of the sloshing wave colliding with its cap. In an impact damper, intentional collisions are encouraged between a small impactor and its slightly larger cavity which is attached on a structure to be controlled. Each collision dissipates energy and causes an exchange of momentum. The configuration of the impact damper in this figure, however, is designed to take advantage of the

*Corresponding author. Tel.: +61-3-9688-4009; fax: +61-3-9688-4139.
E-mail address: eren.semercigil@vu.edu.au (S.E. Semercigil).

doi:10.1016/S0022-460X(02)01488-8

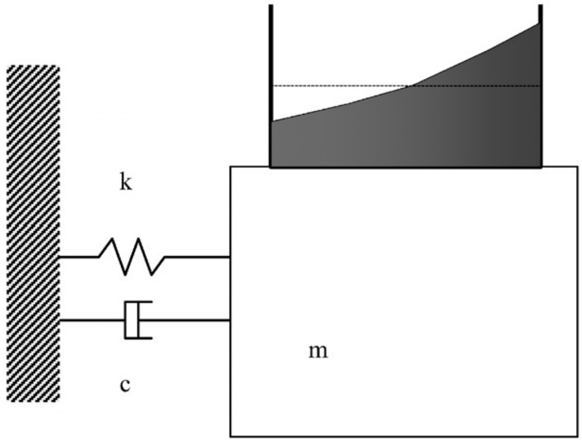

Fig. 1. Showing a single degree-of-freedom oscillator with the sloshing absorber of unrestricted free surface.

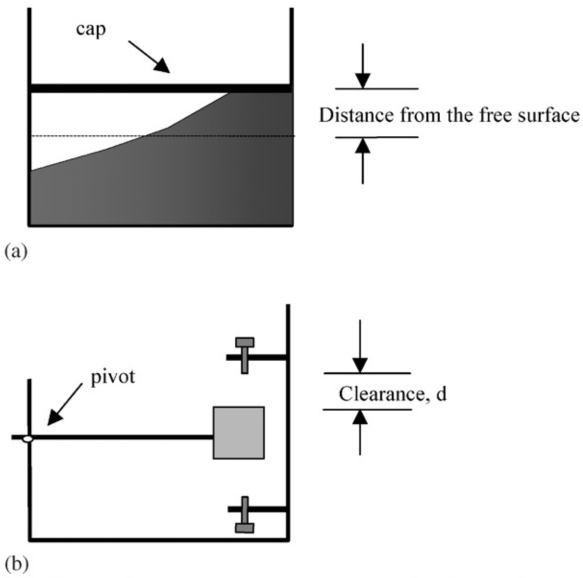

Fig. 2. Showing the sloshing container with (a) the cap and (b) impact damper arrangement.

energy dissipation alone since oscillations of the structure take place in a direction normal to that where the collisions take place. Design of impact dampers has been relatively well understood with Ref. [6] reporting most of the important design parameters.

Experimental observations are reported in this paper to determine the effect of surface restraints of a standing-wave-type sloshing absorber in suppressing structural response. In addition, the performance of the sloshing absorber is compared with that of an impact damper.

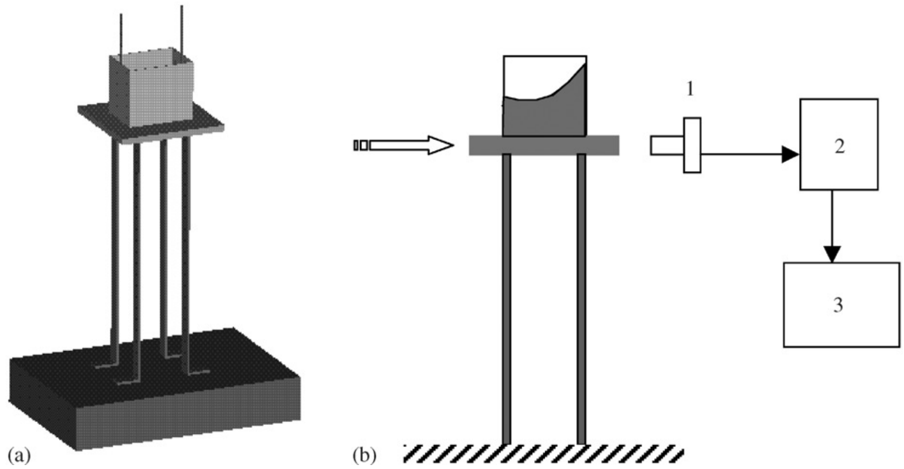

Fig. 3. Experimental set-up, (a) isometric and (b) schematic view. (1) Keyence, LB-12 laser displacement transducer; (2) Keyence LB-72 amplifier and DC power supply; (3) DataAcq A/D conversion board, and Personal Computer.

2. Experiments

An isometric view of the experimental set-up is shown in Fig. 3(a). A rigid platform is cantilevered with light aluminium strips to form a simple oscillator. The platform also provides a flat surface to mount the 75 mm $\times$ 105 mm plastic container of the sloshing absorber. The container has two vertical strips to allow variable gaps between the free surface and the cap. An approximately 30-mm depth of water, across the 75 mm wavelength, was observed to produce a strong interaction with the oscillator's free response. The mass of the container including its liquid content was 400 ± 10 gm.

The natural frequency and the equivalent critical viscous damping ratio of the structure were measured to be 2.7 ± 0.2 Hz and 0.002 ± 0.001, respectively. Equivalent mass of the structure was 4000 ± 10 gm.

Experimental procedure consisted of observing the free decay of the structure after giving it a pre-determined initial displacement. A stop block was used to provide consistent initial displacements. Displacement history of the structure was sensed with a non-contact laser transducer and amplified before it was recorded in a personal computer (items 1, 2 and 3 in Fig. 3(b)). With the sloshing absorber, the experiment was repeated for various gaps between the free surface and the cap, starting with a zero gap to a large enough value to ensure a free sloshing surface. Three different working fluids were used in the absorber, namely water, a light mineral oil and a mineral oil suspension with corn starch (45% solid content by weight).

The experimental procedure discussed above was repeated with the impact damper shown in Fig. 2(b). The impact damper was made of a light aluminium strip pivoted from one of the inside walls of the same plastic container. An aluminium tip mass was attached at the free end, and placed in a cavity attached on the opposite wall. A pair of fine threaded screws provided varying clearances. The tip mass was centred between the screws using counter weights (not shown for clarity). The total added mass of the impact damper was maintained to be 10% of the mass of the structure. The coefficient of restitution of the collisions was estimated to be between 0.4 and 0.6 [6].

3. Results

Displacement history of the uncontrolled oscillator is shown in Fig. 4. The structure has relatively poor dissipation with an equivalent viscous damping ratio of approximately 0.2%, taking well over a minute before its oscillations could settle.

Typical displacement histories are shown in Fig. 5 when water is used as the working fluid of the sloshing absorber. Fig. 5(a) represents the case with zero gap where no sloshing is allowed in the container. Apparent improvement in the response of the structure as compared to that in Fig. 4 is due to two sources, namely the added mass effect and the slight leakage around the cap. The small clearance between the cap and the inside walls of the container allowed some water to splash through and dissipate energy (no gasket was used to seal this small gap).

In Fig. 5(b), the best performance case is given when the gap above the free water surface is 5 mm. For this case, oscillations of the structure stop within approximately 15 s. For the 5 mm gap case, rising waves violently hit the cap above the free surface. As a wave descends, its preceding strong interaction with the cap produces surface breaks to dissipate energy. As a consequence of this dissipation, the control action is quite effective.

When the gap is increased to 25 mm, a drastic deterioration of the control is observed with oscillations taking over 30 s to stop, as illustrated in Fig. 5(c). With increased gap, the interaction of a rising wave with the cap becomes milder than the case in Fig. 5(b). Further increases in the gap changes the response of the structure only marginally (not shown here for brevity). In

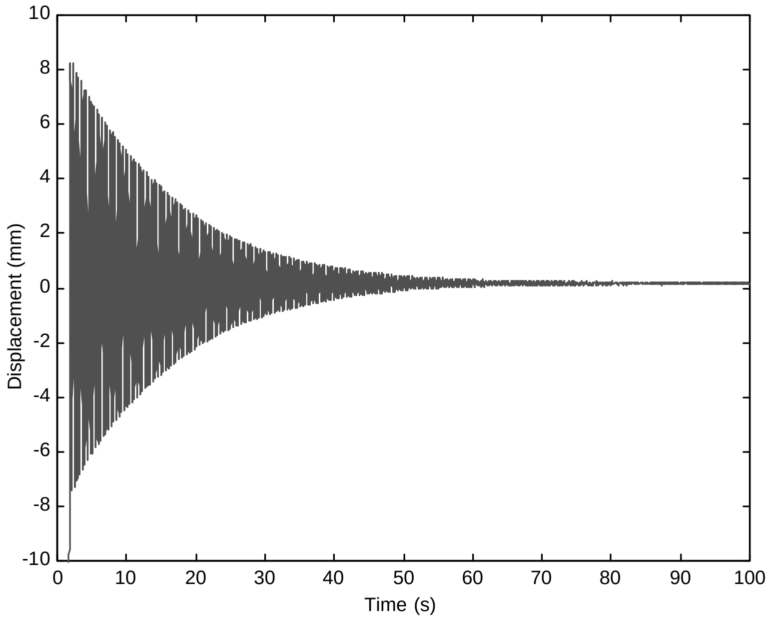

Fig. 4. Uncontrolled displacement history of the structure without sloshing.

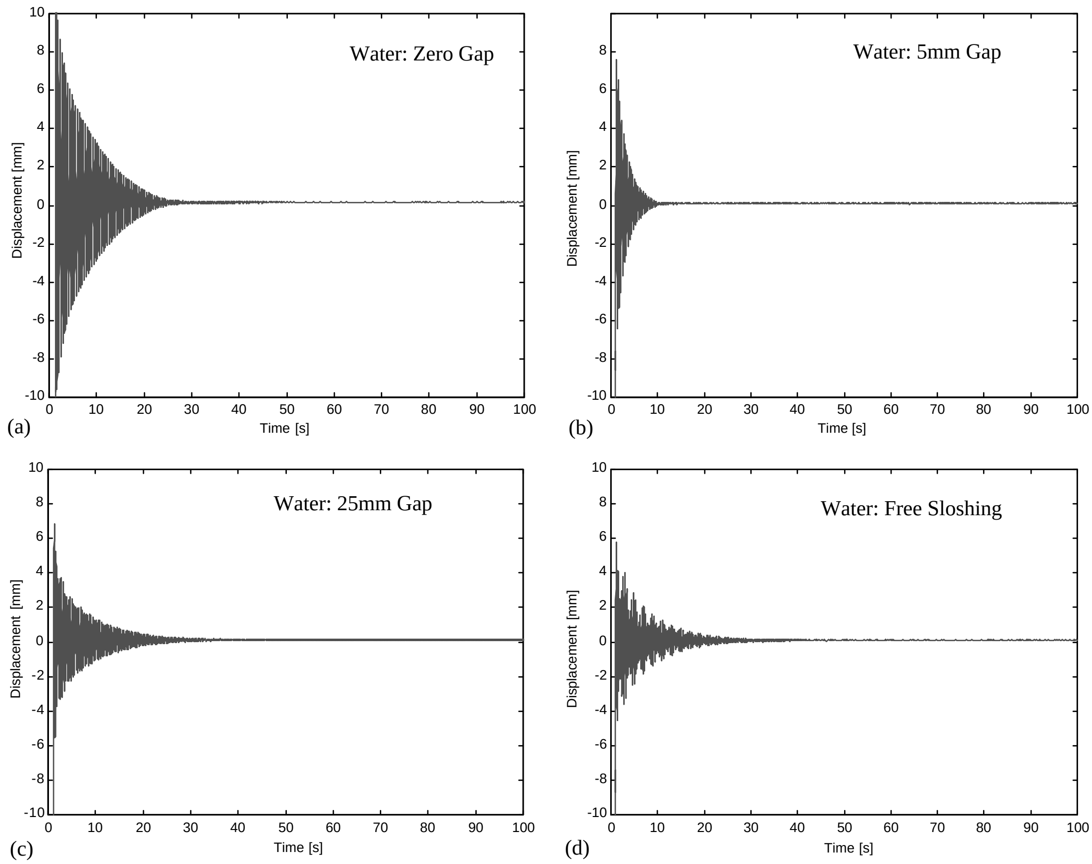

Fig. 5. Displacement history of the structure with water and with (a) zero gap, (b) 5 mm gap (25 mm gap) and (d) free surface.

Fig. 5(d), free surface case is shown with a quite similar settling time to that in Fig. 5(c). For this case, free sloshing wave can reach heights of up to 60 mm with large velocity gradients at the free surface. One significant phenomenon to notice in Fig. 5(d) is the presence of a beat in the envelope of the structure's response. This beat is an indication of a strong interaction between the fundamental sloshing frequency and the structural natural frequency.

First 20 s of the free surface case in Fig. 5(d) are repeated in Fig. 6(a). Fig. 6(b) will be discussed in relation to Fig. 8. Magnitude of the beat envelope is a clear indicator of the location of most of the oscillatory energy. When the beat envelope is at a peak (at approximately 1, 3, 5 s,…), most of the energy is with the oscillator. Hence, peak amplitudes of the beat envelope correspond to temporary calm of the sloshing water. When the beat envelope is at a minimum (at 2, 4, 6 s,…), most of the energy is with the sloshing liquid while the oscillator experiences a temporary calm. Although there is large swings of energy between the two sub-systems, poor energy dissipation allows these large swings to continue for relatively long durations. Interaction with the restraining cap seems to provide enough energy dissipation to suppress the beat.

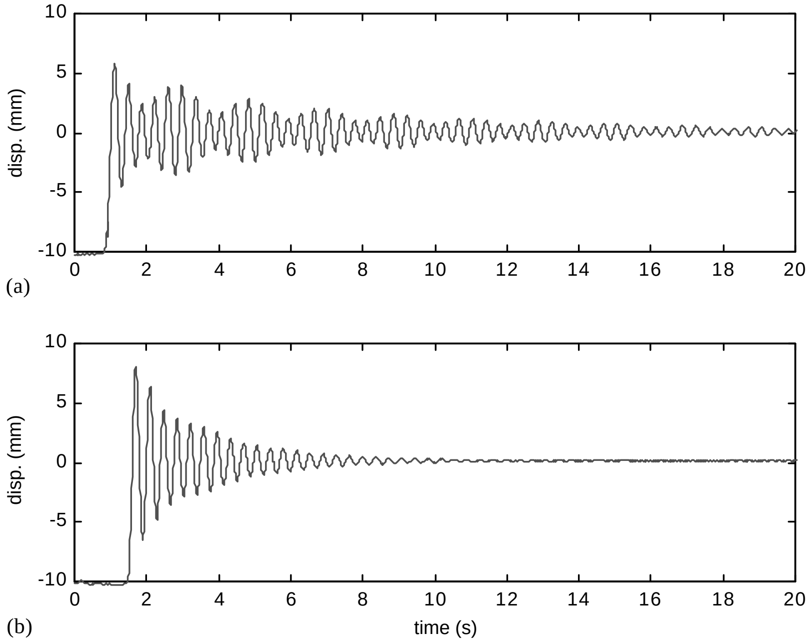

Fig. 6. Displacement history of free surface sloshing with (a) water and (b) ER fluid.

In Fig. 7, results are presented in an identical format to that in Fig. 5 but for a mineral oil instead of water. As expected, Fig. 7(a) is similar to Fig. 5(a). In Fig. 7(b), a 5 mm gap again indicates effective attenuations. For this case, the interaction of the mineral oil with the top plate is much milder than that with water. Descending waves display some mixing but no surface breaks. Therefore, the mechanism of energy dissipation with the mineral oil seems to be predominantly through viscous dissipation. Viscosity of the mineral oil is larger than that of the water by one order of magnitude as indicated in Table 1.

Another significant difference between the mineral oil and water is the relative insensitivity of the mineral oil to varying gap. As the gap increases to 25 mm in Fig. 7(c), the change in the response of the structure is marginal. Even in the free surface case in Fig. 7(d), similar settling times are maintained. For the free surface case, rising sloshing waves reach a maximum of 50 mm, about 20% lower than that with water. Although velocity gradients of the mineral oil are smaller than those of water, there is enough viscous dissipation to maintain effective control. As a consequence of this inherent energy dissipation, no beat is apparent in Fig. 7(d).

In Fig. 8, the results are shown when the same mineral oil is used to suspend corn starch particles with a 45% weight ratio. This suspension liquid was noticed in an earlier study of the authors for its high viscosity [9]. Corn starch suspension in mineral oil is an electrorheological (ER) fluid which can reversibly change its phase from liquid to a solid-like gel when it is exposed to a field strength of about 1 kV/mm.

The response of the structure with the ER fluid is similar to that of the mineral oil. Differences can be observed, however, in the surface patterns of the sloshing liquid. With a 5 mm gap, the interaction of a rising wave with the cap is even milder than that with the mineral oil, producing no surface mixing or discontinuity. In fact, Fig. 2(a) is a close representation of an ER fluid wave

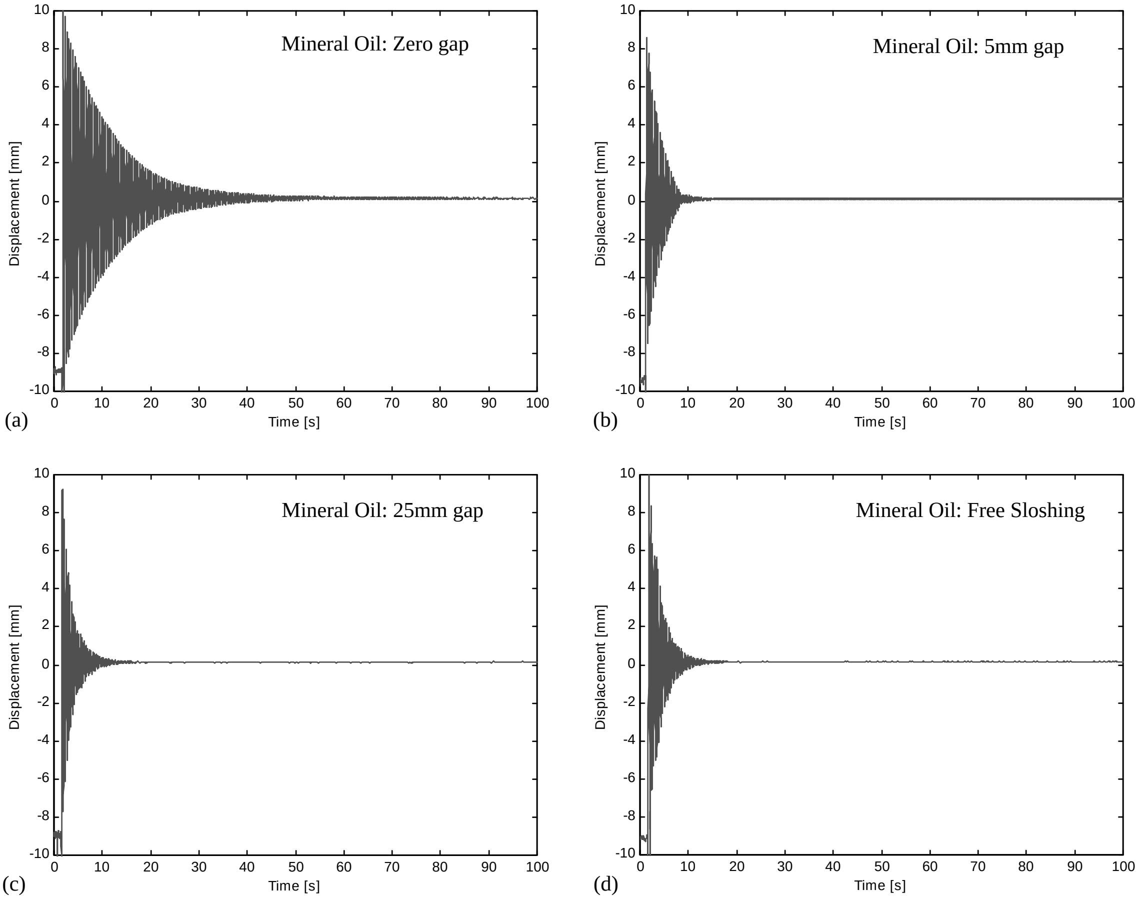

Fig. 7. Same as in Fig. 5 but with mineral oil.

Table 1
Fluid properties at room temperature

	Viscosity (Pa s)	Density (g/ml)
Water	0.001 [7]	1.0
Mineral oil	0.010 ± 0.005	0.84 [8]
ER fluid	0.53 ± 0.01	0.78

interacting with the restricting cap. As the gap increases, similar to the case of the mineral oil, only marginal changes occur in the structure's response.

The free surface sloshing in Fig. 8(d) is repeated in Fig. 6(b) using the same scale as in Fig. 6(a). In Fig. 6(b), in contrast to the beat envelope in Fig. 6(a), the viscous dissipation in the ER fluid results in an envelope with an almost perfectly exponential decay. This decay is equivalent to the decay of a 3% critical damping of the structure.

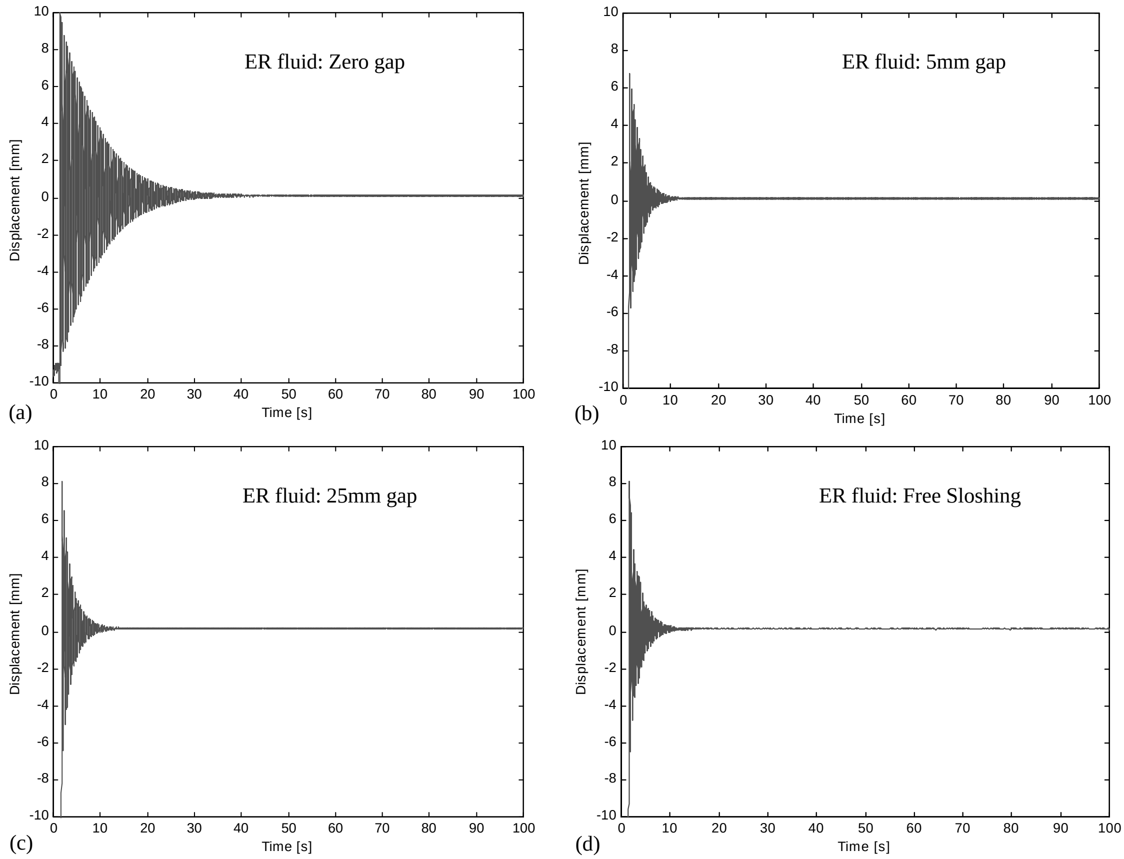

Fig. 8. Same as in Fig. 5 but with ER fluid.

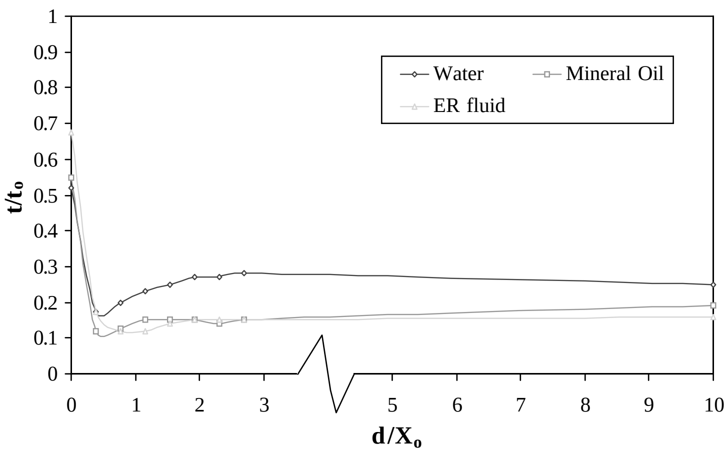

Fig. 9. Variation of settling time ratio with three different sloshing liquids.

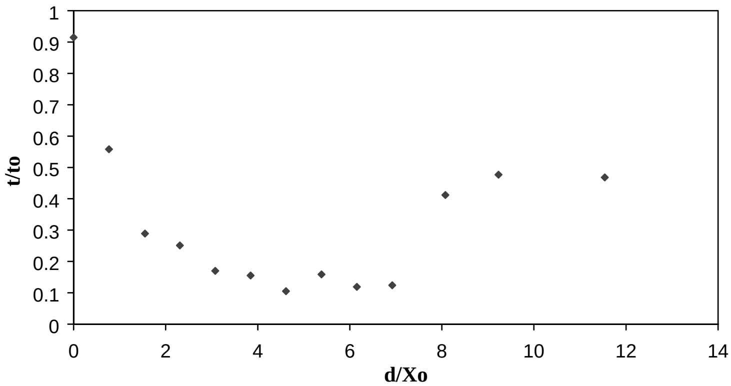

Fig. 10. Same as in Fig. 9 but for the impact damper.

A summary of results is given in Fig. 9 where the 10% settling times of the controlled cases, t, are compared with that of the uncontrolled structure, to. A 10% settling time corresponds to the duration required for the peak displacement to decay to 1/10th of the initial displacement. Hence, the ratio of t/to, should be small to indicate effective control. The horizontal axis represents the variation of the gap, d, non-dimensionalized with the initial displacement Xo.

The smallest t/to of water ($\Diamond$) is about 0.17, representing 83% attenuation. Sloshing water is quite sensitive to the variation in the gap, deteriorating to about 70% attenuation at d/Xo of 2.5 and larger. Both mineral oil (Δ) and ER fluid ($\Box$) are more effective than water, with their best attenuations close to 90%. More importantly, the effectiveness of control is maintained at about 85% attenuation for all values of d/Xo larger than 1. This relative insensitivity is an advantage from a design point of view where maintaining a critical d/Xo may not be possible practically.

Fig. 10 contains the summary of experimental observations with the impact damper discussed earlier. In this figure, the axes are marked the same as in Fig. 9. The only difference is that the non-dimensional clearance of the horizontal axis now represents the ratio of the clearance of the impact damper instead of the gap above the free surface of the sloshing absorber. The most effective attenuations of the settling time correspond to non-dimensional clearances of 4–7. At these clearances, impact damper is able to shorten the 10% settling time of the uncontrolled oscillator by approximately 85%. As the clearance increases to 8 and larger, the attenuations deteriorate rapidly. For these large clearances, even though establishing contact is still possible, approach velocity is too small to be effective. In contrast to large clearances, the frequency of collisions increases for small clearances. But these frequent collisions suffer the same difficulty of small approach speeds. Zero clearance case corresponds to clamping the impact damper with the adjustable screws.

4. Conclusions

Typical results are presented from an experimental investigation to enhance the energy dissipation characteristics of standing-wave-type sloshing absorbers. Restraining caps, placed above the free surface of the sloshing liquid, are used to induce dissipation. When water is used, best attenuation is about 80%. Energy dissipation is accomplished through the strong interaction of rising waves with the restraining cap, and severe surface breaks of descending waves. Light mineral oil and the ER fluid give their best attenuation of around 90%. Moreover, these two liquids are much less sensitive than water to the variations of the gap between the restraining cap and the free surface. With these two liquids, energy dissipation seems to take place through viscous dissipation.

An impact damper of the same mass as the sloshing absorber is observed to be quite effective, with attenuations in the order of 85%. However, performance of the impact damper is dependent quite strongly on the choice of right clearance.

Acknowledgements

T.D. Truong is a recipient of Victoria University Postgraduate Scholarship Award.

References

[1] K. Fuji, Y. Tamura, T. Wakarahara, Wind-induced vibration of tower practical and applications of tuned sloshing damper, Journal of Wind Engineering and Industrial Aerodynamics 33 (1990) 263–272.
[2] M. Abe, S. Kimura, Y. Fujino, Semi-active tuned column damper with variable orifice openings, Third International Conference on Motion and Vibration Control, Chiba, 1996, pp. 7–11.
[3] S. Kaneko, O. Yoshida, Modelling of deep water type rectangular tuned liquid damper with submerged nets, Sloshing Fluid-Structure Interaction and Structural Response Due to Shock and Impact Loads, ASME, PVP-Vol. 272, 1994, pp. 31–42.
[4] M.L. Seto, V.J. Modi, A numerical approach to liquid sloshing dynamics and control of fluid-structure interaction instabilities, The American Society of Mechanical Engineers Fluids Engineering Division Summer Meeting, Paper No. FEDSM97-3302, 1997.
[5] J.G. Anderson, S.E. Semercigil, Ö.F. Turan, A standing-wave type sloshing absorber to control transient oscillations, Journal of Sound and Vibration 232 (5) (2000) 839–856.
[6] C.N. Bapat, S. Sankar, Single unit impact damper in free and forced vibration, Journal of Sound and Vibration 99 (1985) 85–94.
[7] F.L. White, Fluid Mechanics, 3rd Edition, McGraw-Hill, New York, 1994.
[8] Supplier information, Sceney Chemicals Pty., Ltd., Sunshine, Victoria, Australia, 2001.
[9] T. Truong, S.E. Semercigil, A variable damping tuned absorber with an electro-rheological fluid for transient resonance of light structures, Journal of Sound and Vibration 239 (5) (2001) 891–905.