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Using Free and Restricted Sloshing Waves for Control of Structural Oscillations

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Abstract

Sloshing is the large amplitude and low frequency oscillation of a liquid in a partially filled container. It is normally desired to suppress sloshing to prevent its detrimental effects on the safety of its container. Alternatively, intentionally induced sloshing may be used to passively control structural vibrations. The use of sloshing as a structural controller is similar to the use of a classical tuned vibration absorber. The advantage of the sloshing absorber over the tuned absorber is its simplicity, especially for cases where a liquid container has to be accommodated as part of a structure such as a water tower.

This paper summarises the results of an extensive experimental study on the effectiveness of a sloshing container as a vibration controller. Water, a light mineral oil and mineral oil suspension, were used as sloshing liquids. The container geometries allowed either a free sloshing wave or a restricted wave with a cap located at varying distances from the free surface. Results demonstrate the parameters required for optimal structural control.

Introduction

In many practical applications, it is critical to suppress liquid sloshing to avoid its detrimental effects. Alternatively, sloshing may be induced intentionally to control excessive structural vibrations. This concept was suggested earlier by Fujii et al. [1], Abe et al. [2], Kaneko and Yoshida [3] and Seto and Modi [4]. These works dealt with shallow liquid levels which result in a traveling sloshing wave. Traveling waves are preferable to standing waves because of their better energy dissipation characteristics. The poor energy dissipation characteristics of standing waves have been reported earlier [3,5].

Deep liquid levels are important practically as they more realistically represent storage containers. Again, it is practically important to use these containers for structural control purposes as they may already exist as part of the structure to be controlled. The control effort may then be reduced to designing these containers for improved control purposes, rather than prescribing additional components. What is reported here is a summary of extensive experiments to investigate the effective control parameters of a standing-wave type sloshing absorber. To the best of the authors' knowledge, this work is only the second attempt in this direction, following that of Reference 5.

In Figure 1, a simple mechanical oscillator is shown with a container partially filled with a liquid, representing the sloshing absorber. It is desired to design the container dimensions such that there is strong interaction between the sloshing liquid and the oscillator to achieve an effective control. A standing-wave type sloshing absorber normally has poor energy dissipation even when there is a strong interaction. This poor energy dissipation leads to a beating envelope in the response of both the structure and the liquid [5]. A cap placed above the free surface of the liquid may partially restrain the surface wave, possibly improving the rate of energy dissipation. In Figure 2, this suggested configuration is illustrated. Experimental observations are reported in this paper to determine the effect of such restraints in suppressing structural response quickly.

The next section includes a brief description of the parameters of the structure, the sloshing absorber and the experimental procedure. Then, typical results are discussed to indicate important parameters.

Experiments

An isometric view of the experimental setup is shown in Figure 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 container (75x105x100 mm) of the sloshing absorber which has two vertical adjusting strips to allow variable gaps of the surface plate. An approximately 30-mm depth of water has produced strong interaction between the sloshing liquid and the structure. The fundamental frequency of the structure is 2.7 Hz. The mass of the sloshing liquid is maintained to be 10% of the mass of the structure to be controlled. Structural parameters and fluid properties are summarized in Table 1.

The experimental procedure consisted of observing the free decay of the structure after giving it a initial displacement of 13 ± 0.5 mm. The 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 Figure 3(b)). The experiment was repeated from a zero gap to a large enough value to ensure free surface response. Water, a light mineral oil and mineral oil suspension with corn starch (45% solid content) were used as working liquids in the absorber.

Displacement history of the oscillator without sloshing is shown in Figure 4. The structure had relatively poor dissipation with an equivalent viscous damping ratio (ζ_{eq}) of approximately 0.2%, taking well over a minute before its oscillations could settle. The objective of the experiments was to determine the parameters of the sloshing absorber to shorten this long settling time.

Results

Typical displacement histories are shown in Figure 5 when water was used as the working fluid of the sloshing absorber. Figure 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 the uncontrolled one in Figure 4, is primarily due to the added mass effect. In Figure 5(b), the best performance case is given when the gap above the free water surface is 5mm. For this case, oscillations of the structure stop in less than 15 seconds.

For the 5 mm gap case, rising water waves hit the plate above the free surface violently. As a wave descends, its preceding strong interaction with the plate produces surface breaks to dissipate energy. As a consequence of this dissipation, the control action on the structure is quite effective.

When the gap is increased to 25 mm, a drastic deterioration of the control is observed with oscillations taking over 30 seconds to stop, as illustrated in Figure 5(c). With increased gap, the interaction of a rising wave with the plate becomes milder than the case in Figure 5(b). Further increases in the gap changes in the response of the structure only marginally (not shown here for brevity). In Figure 5(d), free surface case is shown with a quite similar settling time to that in Figure 5(c). For this case, a rising sloshing wave can reach heights of up to 60 mm with large velocity gradients at the free surface. One significant phenomenon to notice in Figure 5(d), as compared to the other three frames, is the presence of a beat in the envelope of the structure's response. This beat is an indication of tuning between the fundamental sloshing frequency and the structural natural frequency.

In Figure 6, results are presented in an identical format to that in Figure 5, but for a mineral oil as the working liquid instead of water. As expected, Figure 6(a) is similar to Figure 5(a). In Figure 6(b), a 5 mm gap again indicates effective attenuations. However, the interaction of the mineral oil with the top plate is much milder than that with water. As a result, descending waves display fewer surface discontinuities than in the case with water. The free surface with the mineral oil still shows some mixing but without surface breaks. Therefore, despite a comparable control effect on the structure, the mechanism of energy dissipation with the mineral oil is quite different than it is with water. It is expected that energy is lost through viscous dissipation with the mineral oil due to its increased viscosity by an order of magnitude. Fluid properties are listed in Table 1.

Another significant difference between the mineral oil and water is in the sensitivity of the control to varying gap. As the gap increases to 25 mm in Figure 6(c), the change in the response of the structure is marginal, with similar settling times even in the free surface case in Figure 6(d). For the free surface case, rising sloshing waves reache 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 a large enough viscous dissipation to maintain effective control. As a consequence of this inherent energy dissipation, no beat is apparent in Figure 6(d).

In Figure 7, the results are shown when the same mineral oil is used to suspend corn starch with a 40% weight ratio. This liquid mixture was noticed in an earlier study of the authors for its high viscosity, as indicated in Table 1. 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 a large enough electric potential (about 1kV/mm) is applied to it.

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 plate is even milder than that with the mineral oil, producing no surface discontinuities at all. Figure 2 is a close representation of the ER fluid wave with the restricting plate. As the gap increases, again similar to the case of the mineral oil, the change in the structure's response is marginal.

A summary of results is given in Figure 8 where the 10% settling times of the controlled cases, t, are compared with that of the uncontrolled structure, to. 10 % settling time corresponds to the duration required for the peak displacement to decay 1/10 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, nondimensionalised with the initial displacement Xo.

The smallest t/to of water (◊) 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 ( ) are more effective than water with 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 a great advantage from a design point of view where maintaining a critical d/Xo may not be possible practically in the field.

Conclusions

Some typical results are presented from an extensive experimental investigation to enhance the energy dissipation characteristics of standing-wave type sloshing absorbers. Restraining plates, placed above the free surface of the sloshing liquid, are used to induce dissipation. When water is used, best attenuation is about 80% with a 10% mass ratio between the absorber and the structure. Energy dissipation is accomplished through the strong interaction of rising waves with the restraining plate, and severe surface breaks of descending waves. Other two liquids, a light mineral oil and ER fluid, gave best attenuation of 90%. Moreover, these two liquids are much less sensitive to the variations of the gap between the restraining plate and the free surface. With these two liquids, energy dissipation is expected to occur more through viscous dissipation than interaction with the plate. This work is part of an ongoing study to investigate the mechanisms of energy dissipation with different sloshing liquids for structural control.

Acknowledgement

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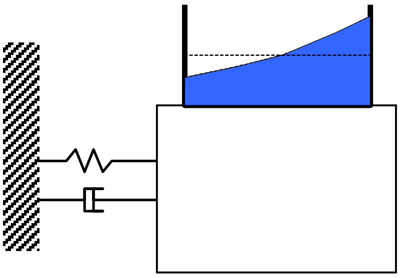

Figure 1 Showing a single degree-of-freedom oscillator with the sloshing absorber of unrestricted free surface

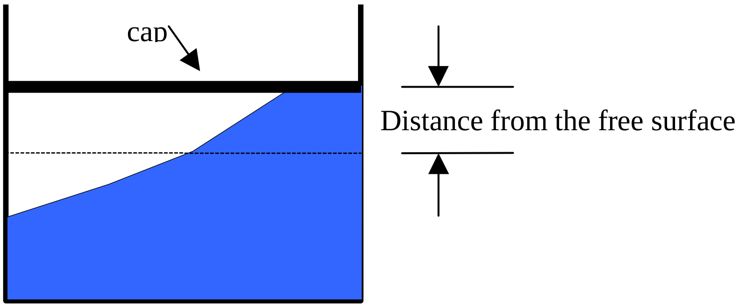

Figure 2. Showing the sloshing container with the cap.

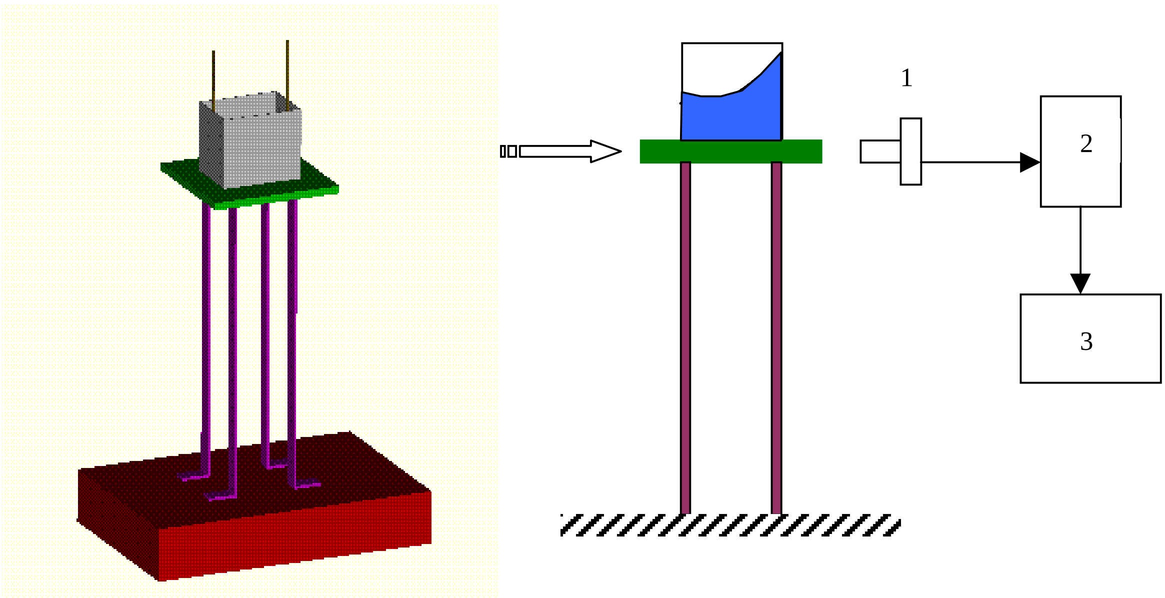

Figure 3. Experimental setup, (a) isometric and (b) schematic view . 1: Keyence, LB-12 laser displacement transducer; 2 :Keyence LB-72 amplifier and DC power supply;3: DataAcq A/D conversion board, and Personal Computer

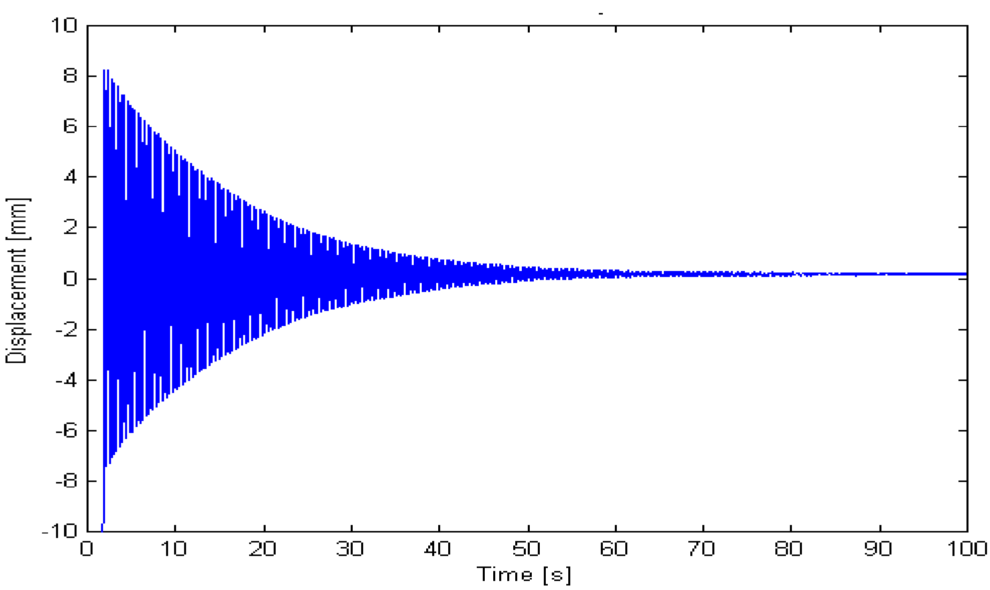

Figure 4. Uncontrolled displacement history of the structure without sloshing.

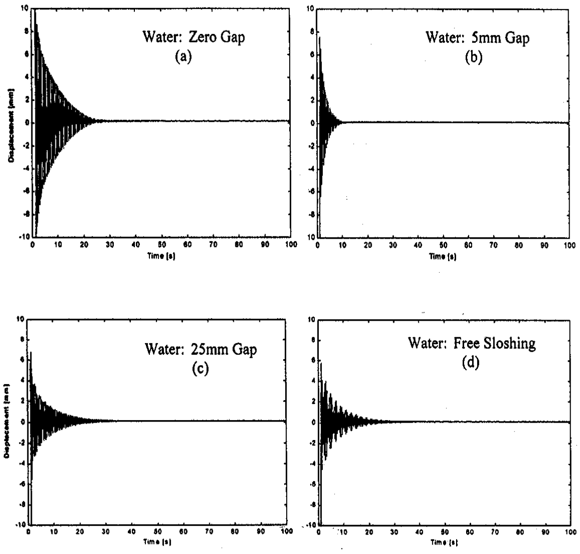

Figure 5. Displacement history of the structure with water and with (a) zero gap, (b) 5 mm gap, (25 mm gap and (d) free surface.

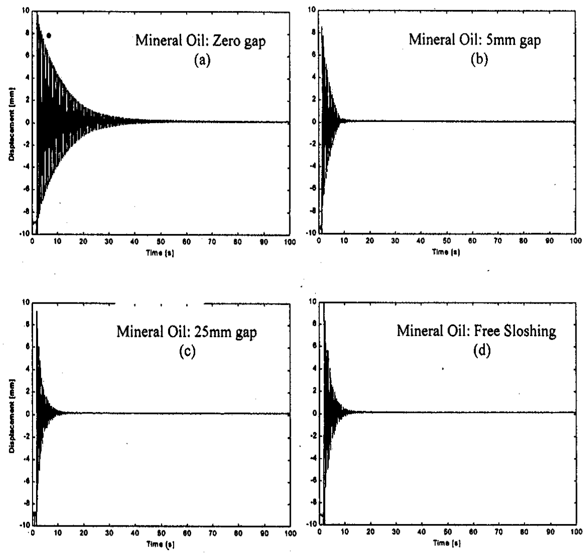

Figure 6. Same as in Figure 5 but with mineral oil.

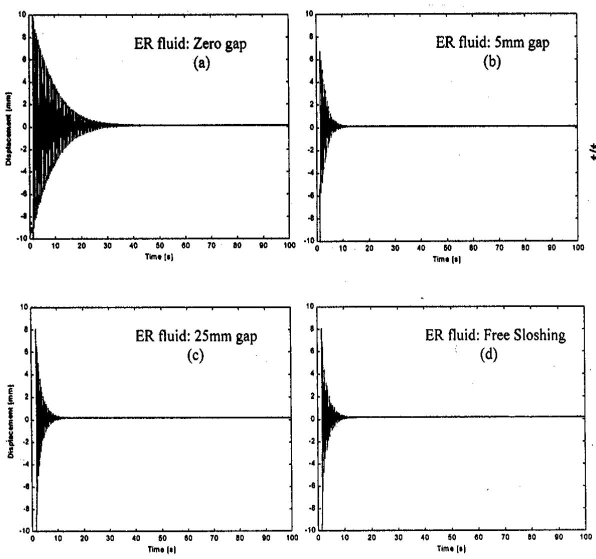

Figure 7. Same as in Figure 5 but with ER fluid.

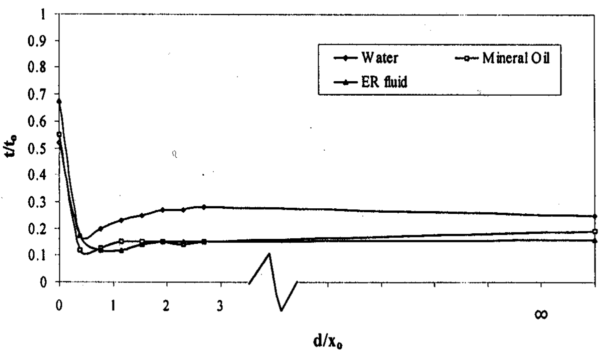

Figure 8. Variation of settling time ratio with gap

	mass (±0.01kg)	Stiffness (N/m)	ξ eq	Viscosity (Pa s)	Density (g/ml)
Structure	4.0	1150	0.002 ±0 .001	–	–
Water	0.4	–	–	0.001 [6]	1.0
Mineral oil	"	–	–	0.010 ± 0.005	0.84 [7]
ER-susp.	"	–	–	0.53 ± 0.01	0.78

Table 1. Structural and fluid properties (at room temperature).