Journal of Sound and Vibration (2001) **240**(2), 398–404
doi:10.1006/jsvi.2000.3121, available online at http://www.idealibrary.com on IDEAL®

EXPERIMENTS TO CONTROL SLOSHING IN CYLINDRICAL CONTAINERS

J. G. ANDERSON, Ö. F. TURAN AND S. E. SEMERCIGIL

School of the Built Environment (Mechanical Engineering), Victoria University of Technology, Footscray Campus, P.O. Box 14428 *MCMC, Melbourne, Victoria* 8001, *Australia.*
E-mail: eren@dingo.vu.edu.au

(*Received* 28 *March* 2000, *and in final form* 5 *June* 2000)

1. INTRODUCTION

The detrimental effects of liquid sloshing are experienced in a number of areas, including the transportation of liquid cargo, storage of liquid in tanks and handling of molten metal in casting operations. Sloshing may spoil sensitive items, such as suspension-type food, wine and chemical liquids during transportation. Liquid sloshing can cause loss of dynamic stability and maneuverability of the transportation vehicle. In earthquake prone parts of the world, liquid sloshing due to ground motion can cause spillage and lead to structural failure. Therefore, it is important to control sloshing to prevent loss of life and property.

Warnitchai and Pinkaew [1] predicted the effect of flow damping devices on sloshing in rectangular tanks. In their formulation, the liquid was assumed to be inviscid, incompressible and irrotational. Surface tension effects were ignored. Their numerical model was used to determine the effects of vertical poles, baffles and nets on controlling liquid sloshing. A number of other methods exist to control liquid sloshing in cylindrical containers. Hayama and Iwabuchi [2] used the momentum of liquid in an inverted U-tube to suppress sloshing. Reference [3] used submerged blocks and plates placed strategically in a container to successfully suppress sloshing. The disadvantage of these approaches is that suppression occurs at a critical liquid height, and therefore, variation in liquid height reduces the effectiveness of the controllers. Hara and Shibata [4] actively injected air bubbles into the liquid. The timing of injection was critical and needed to be at the instant that the sloshing wave was ascending from the lowest position to the equilibrium position.

Some of the other works published on liquid sloshing investigated the range of Reynolds numbers on the effect of viscosity of the liquid [5, 6]. Another approach on the use of sloshing has been to use it as a means to control structural oscillations, such as in references [7–10]. In this particular approach, work is directed towards encouraging the sloshing action rather than suppressing it.

In this paper, a simple control device consisting of two plates in a dumb-bell arrangement [11] is evaluated experimentally for the control of liquid sloshing in rigid cylindrical containers. The dumb-bell controllers are not fixed to the container, rather they are free floating in the liquid. Therefore, they are promising for add-on type of passive sloshing control in tanks that are already in service. The dumb-bell controllers are simpler than the active controllers reported previously.

0022-460X/01/070398 + 07 $35.00/0

Different than what was presented in reference [11], a comprehensive parametric study is presented here. Attention is focused on the ratio of the mass of the controller to that of the liquid to be controlled. In addition, results are presented for a horizontal cylinder which represents a geometry similar to those of road tankers carrying liquid cargo.

2. EXPERIMENTS

In the present study, a vertical container of 100 mm diameter and a horizontal container of 100 mm diameter and 300 mm length were tested on a shaking table. The working fluid was water. The static liquid height was kept constant at 75 mm in the vertical container and 63 mm in the horizontal container. The horizontal container was divided into three compartments of approximately 100 mm length, exposing a rectangular-free surface area for each compartment. This three-compartment arrangement made it possible to observe the controlled and uncontrolled responses simultaneously by leaving at least one of the compartments without a controller.

The experimental procedure consisted of exciting the container and measuring the sloshing wave amplitudes for controllers of differing geometries. Sloshing was induced by the sinusoidal motion created by an electromagnetic shaker and signal generator. The peak-to-peak stroke length of the shaking table was 2 mm for the vertical cylinder. For the horizontal cylinder, the stroke length was varied to produce an uncontrolled wave height that reached the top of the container. The frequency of excitation was kept at the fundamental sloshing frequency, which was 2·8 Hz for both containers. This value is in agreement with the Milne–Thomson approach [12]

$$f_n = \frac{1}{2\pi}\sqrt{\frac{\pi g}{d}\tanh\frac{\pi H_w}{d}}, \tag{1}$$

where g is the gravitational acceleration, d is the container diameter for the vertical cylinder and the partition length for the horizontal cylinder; H_w is the stationary water height. The unit of f_n is Hz.

Flow visualization was achieved by video recording the experiment. The viewed image was scaled appropriately to enable measuring the peak-to-peak sloshing amplitude of the surface with an estimated accuracy of within $\pm 0{\cdot}5$ mm. A schematic diagram of the experimental set-up is shown in Figure 1(a) for the vertical container tests. The horizontal container was excited along its axis using an identical arrangement to that in Figure 1(a). The geometry of the horizontal container is shown in Figure 1(b).

The controllers consisted of two plates separated by rigid rods. The plates were made from 3 mm thick plywood, and the surfaces of the plates were sealed with varnish. The top plate floated on the free surface, whereas the bottom plate was immersed in the water during the experiments. To ensure maximum interference with the sloshing surface wave, circular plates were used in the vertical container and rectangular plates were used in the horizontal container as shown in Figure 2. For all the vertical trials and for some of the horizontal trials, the centers of the plates were hollowed out to reduce weight. The hollow square plates had a constant thickness, t, of 20 mm, and the thickness of the round plates was varied. The dumb-bell-shaped controllers are positively buoyant when floated on the liquid-free surface, having an equilibrium position, as illustrated in Figure 3(a). However, when the top plate is forced down into the liquid surface, the controller remains at the second equilibrium position shown in Figure 3(b). If the top plate is forced below the surface, the dumb-bell returns to the second equilibrium position.

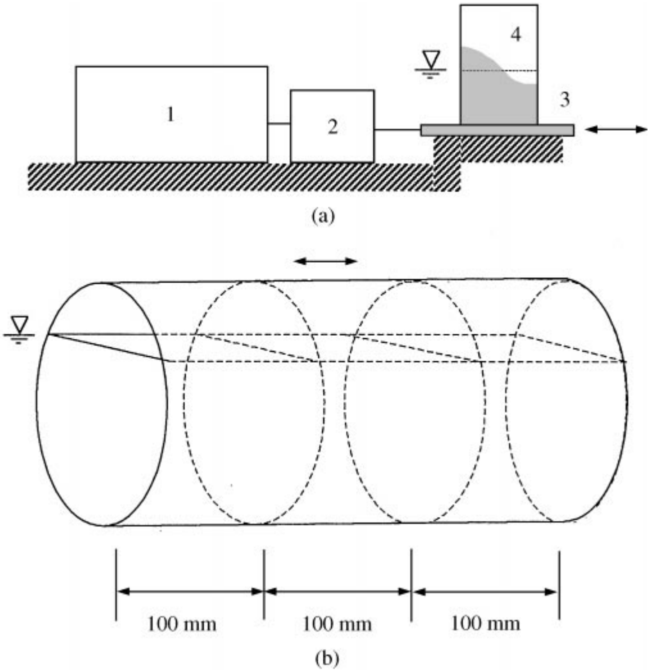

Figure 1. Schematic diagram of (a) the experimental set-up with the vertical container and (b) the horizontal container. 1, SS100 signal generator and amplifier; 2, electromagnetic shaker; 3, shaking table; 4, cylindrical glass container (vertical).

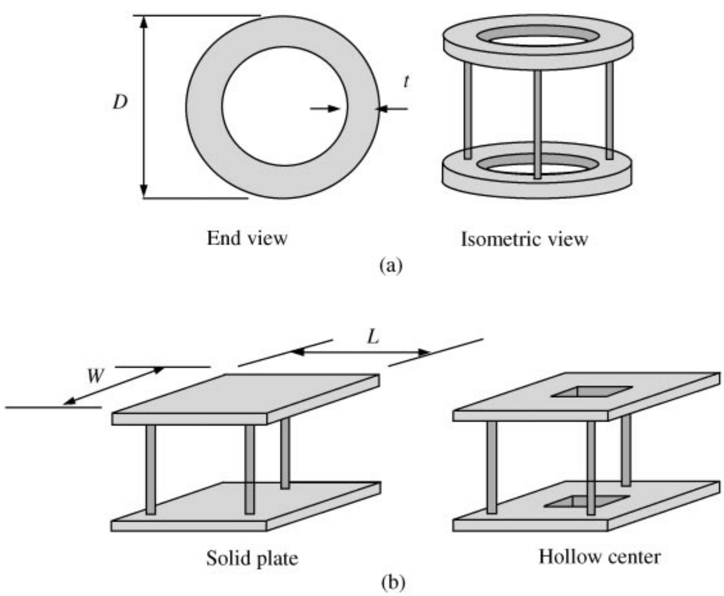

Figure 2. Controllers used in (a) the vertical and (b) the horizontal containers.

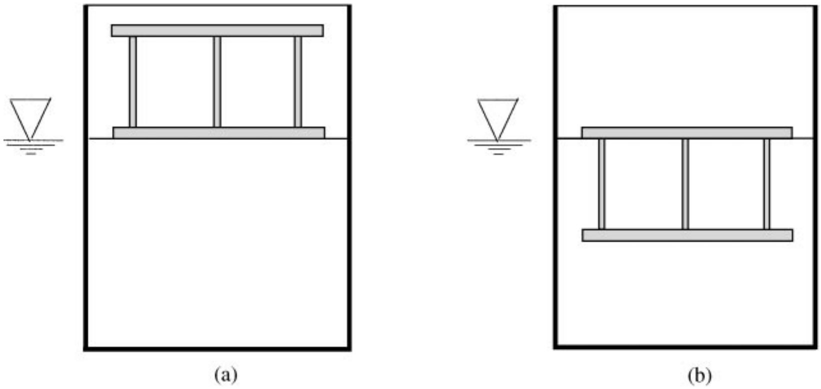

Figure 3. Showing the equilibrium positions of the dumb-bells when the bottom plate is (a) floating on the surface and (b) immersed in liquid.

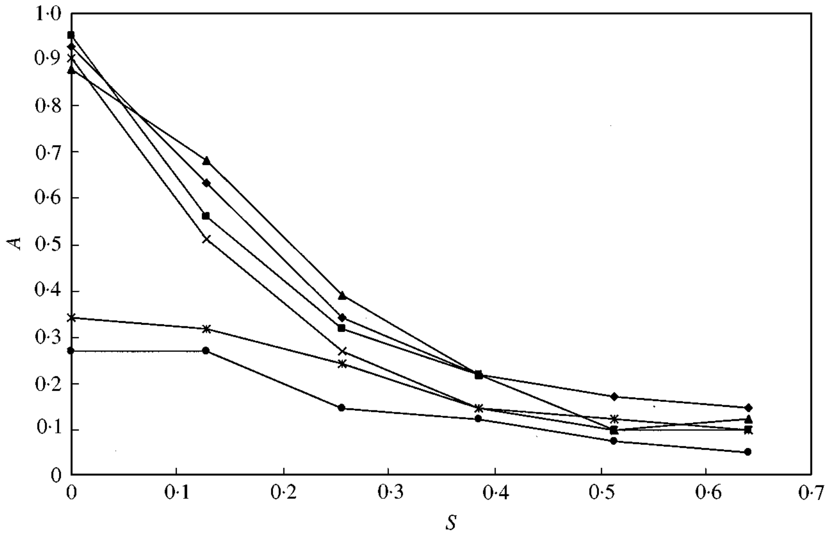

Figure 4. Variation of non-dimensional sloshing amplitude, A, with non-dimensional separation distance, *S*, for the vertical container. Each symbol corresponds to a set of plates with an outer diameter, *D*, and plate thickness, *t*, in mm. —◆—, D70,t10; —■—, D70,t15; —▲—, D80, t10; —×— , D80, t15; —✱—, D97, t10; —●—, D97, t15.

3. RESULTS

The results obtained with the vertical container are shown in Figure 4. In this figure, different symbols indicate different dumb-bell arrangements. The numbers following the letters *D* and *t* indicate the diameter and thickness, respectively, in mm. *A* is the non-dimensional sloshing amplitude, defined as the ratio of the peak-to-peak sloshing amplitudes with the controller to without the controller. *A* of unity represents uncontrolled sloshing. *S* is the non-dimensional ratio of the separation distance between the dumb-bell plates to the static water height.

The results in Figure 4 suggest that, at a critical value of the separation, the immersed bottom plate may act as an anchor for the top plate floating on the free surface. This critical

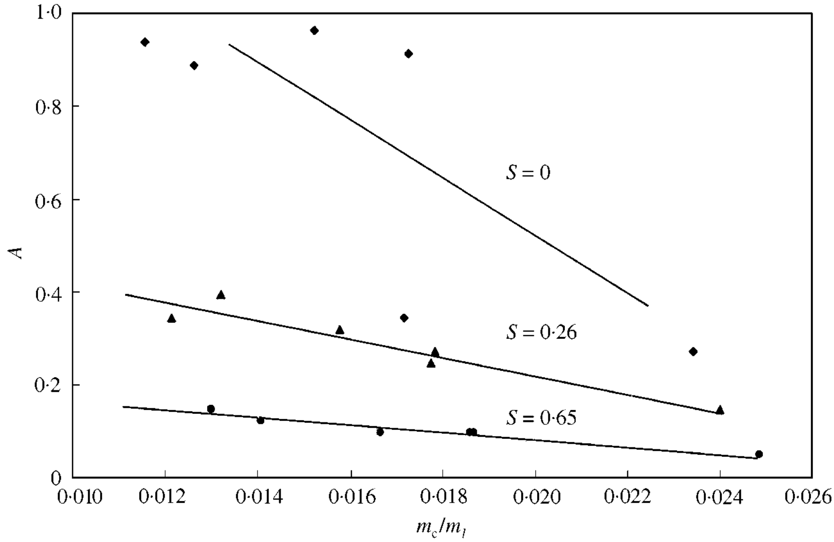

Figure 5. Effect of mass ratio on the sloshing wave at different gaps of the dumb-bell plates (*S*), of 0, 0·26 and 0·65.

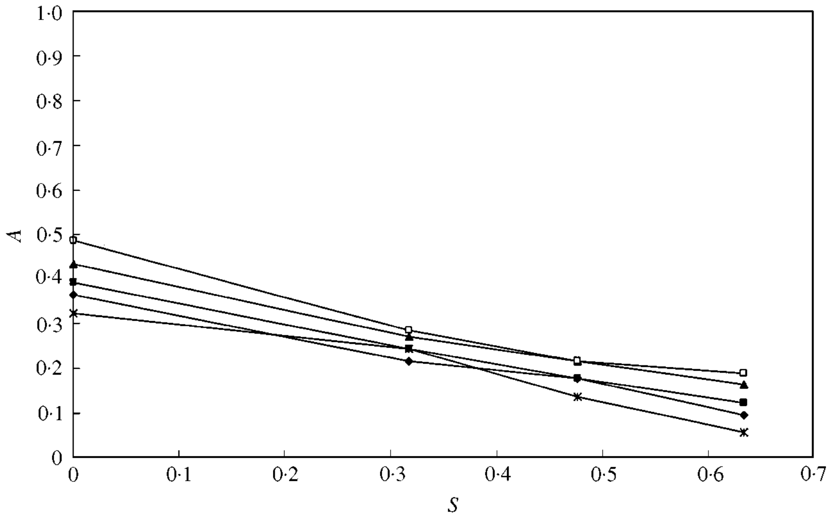

Figure 6. Variation of non-dimensional sloshing amplitude, *A*, with non-dimensional separation distance, *S*, for the horizontal container. Each symbol corresponds to a set of rectangular plates with a length *L*, and width *W*, in mm. *H* denotes hollow plates with a constants 20 mm thickness. —◆—, L80, W70; —■—, L80, W70, H; —▲—, L70, W60; —□—, L70; W60, H; —✳—, L85, W80.

value is around an *S* of 0·5, which corresponds to a reduction of at least 80% ($A \cong 0{\cdot}2$) of the uncontrolled sloshing amplitude. Further increase in *S* produces quite marginal improvement of the control action. This trend suggests that an inertial liquid region may exist at a critical depth. When the bottom plate is immersed in this region, it provides maximum anchoring effect to the top plate. The presence of a deep liquid layer in rigid-body motion is mentioned also in reference [13]. The results in Figure 4 further suggest that, starting with a non-dimensional separation distance, *S*, of approximately 0·25 will allow up to 75% of the liquid to be emptied while maintaining 60% or better sloshing amplitude suppression ($A \leqslant 0{\cdot}4$). As the liquid level drops, the value of S will increase, therefore producing smaller values of A and more effective suppression.

Experimental observations presented in Figure 4 indicate the critical importance of the separation between the plates for effective control. For different plate configurations, however, it is not possible to maintain the same mass of the controlling dumb-bell device. The results in Figure 4 are presented in a different format in Figure 5, in order to separate the effects of mass and separation distances. The vertical axis in Figure 5 is the same as in Figure 4. The horizontal axis represents the ratio of the controller mass to the sloshing liquid mass, m_c/m_l. The results are grouped for three particular S values of 0, 0·26 and 0·65 (corresponding to 0, 20 and 50 mm separation distances), and a best line fit is shown for demonstration purposes for each S.

For increasing values of S, the control effect improves. For any given mass ratio, along a vertical line, the effectiveness of suppression is significantly larger for larger S. In addition, as S increases, incremental improvement in A diminishes. As suggested earlier, beyond an S of 0·5, no detectable difference could be observed in the effectiveness of sloshing suppression.

The results for the horizontal container are presented in Figure 6, in a similar format to that in Figure 4. The numbers following the letters L and W indicate the length and the width of the rectangular plates in mm, respectively, with H indicating hollow plates. For the horizontal container, the controlled sloshing amplitude was approximately linearly proportional to the separation between the two plates. The sloshing was reduced by at least 80% ($A \cong 0{\cdot}2$) when the plate separation was approximately 60% of the static free surface height of the liquid ($S \cong 0{\cdot}6$). The reason why a plateau, similar to that in Figure 4 for values of S larger than 0·5, could not be observed can be explained by the shape of the bottom of the container. As S increases, the lower plate is immersed in smaller volumes of water, and consequently, anchoring effectiveness decreases. Hence, a critical depth may not exist for a horizontal cylinder, as clearly as for a vertical cylinder.

4. CONCLUSIONS

The experimental results presented in this paper show that dumb-bell-type controllers are effective in suppressing sloshing wave amplitudes. For a vertical container, a critical plate separation exists where any further increase can produce only slight improvement of control. For a horizontal container, the reduction in sloshing amplitude is almost linearly proportional to the separation between the two plates. The dumb-bell-type controllers hold promise for practical applications. They are versatile, inexpensive and easy to implement as add-on type of passive control for violent liquid sloshing in cylindrical containers.

REFERENCES

1. P. Warnitchai and T. Pinkaew 1998 *Engineering Structures* **20**, 593–600. Modelling of liquid sloshing in rectangular tanks with flow-dampening devices.
2. S. Hayama and M. Iwabuchi 1986 *Bulletin of JSME* **29**, 1834–1841. A study on the suppression of sloshing in a liquid tank (1st report, suppression of sloshing by means of a reversed U-tube).
3. K. Muto, Y. Kasai, and M. Nakahara 1988 *Transactions of the ASME Journal of Fluids Engineering* **110**, 240–246. Experimental tests for suppression effects of water restraint plates on sloshing of a water pool.
4. F. Hara and H. Shibata 1987 *JSME International Journal* **30**, 318–323. Experimental study on active suppression by gas bubble injection for earthquake induced sloshing in tanks.

5. R. L. Bass, E. B. Bowles, R. W. Trudell, J. C. Peck, N. Yoshimura, S. Endo and B. F. M. Pots 1985 *Transactions of the ASME Journal of Fluids Engineering* **107**, 272–280. Modelling criteria for scaled LNG sloshing experiments.
6. G. Popov, S. Sankar, T. S. Sankar and G. H. Vatistas 1993 *Proceedings of the Canadian Institution of Mechanical Engineers* **207**, 300–406. Dynamics of liquid sloshing in horizontal cylindrical road containers.
7. V. J. Modi and F. Welt 1984 *ASME Winter Annual Meeting*, Vol. **1**, 173–187. Nutation dampers and suppression of wind-induced instabilities.
8. F. Welt and V. J. Modi 1992 *Mechanical Engineering Department*, *University of British Columbia*, *Canada*. Vibration damping through liquid sloshing, Part 1: A nonlinear analysis.
9. K. Fuju, Y. Tamura, T. Sato and T. Wakahara 1990 *Journal of Wind Engineering and Industrial Aerodynamics* **33**, 263–272. Wind-induced vibration of towers and practical applications of tuned sloshing damper.
10. Y. Fujino and L. M. Sun 1993 *ASCE Journal of Structural Engineering* **119**, 3482–3502. Vibration control by multiple tuned liquid dampers.
11. R. Sharma, S. E. Semercigil, and Ö. F. Turan 1992 *Journal of Sound and Vibration* **155**, 360–370. Floating and immersed plates to control sloshing in a cylindrical container at the fundamental mode.
12. L. M. Milne-Thomson 1968 *Theoretical Hydrodynamics*. London: Macmillan Press, fifth edition, 427–442.
13. S. Silverman and H. N. Abramson 1966 *The Dynamic Behavior of Liquids in Moving Containers*, H. N. Abramson editor, NASA SP-**106**, 13–78. Lateral sloshing in moving containers.