17th Australasian Fluid Mechanics Conference
Auckland, New Zealand
5-9 December 2010

Analysing an Efficient Liquid Sloshing Absorber for Vibration Control Using SPH

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Abstract

Tall structures, such as towers and bridges, are subject to wind and earthquake loads which can cause them to oscillate at excessive magnitudes. Liquid sloshing absorbers can be used to suppress these excessive oscillations by tuning the frequency of the sloshing to the critical frequency of the structure to be controlled. These absorbers are simple devices consisting of a partially full container with a free surface. Tuning ensures that significant amounts of harmful energy can be extracted from the structure to the sloshing liquid. However, there needs to be a rapid means of dissipating this energy to avoid its returning back to the structure (then back to the liquid periodically).

Earlier work demonstrated the superior energy dissipation efficiency of a rectangular liquid damper through the introduction of obstructions [7]. A parametric free-vibration study was undertaken giving an increase of up to 60% energy dissipation in the presence of the obstruction. However no analysis was undertaken to experimentally verify the data. As a result suggested experimental optimum ratios given in [7] for damper container dimensions, liquid depth and obstruction height have been analysed here numerically using Smoothed Particle Hydrodynamics (SPH) and reported in the form of design recommendations.

Introduction

Tall structures, such as towers and bridges, are subject to wind and earthquake loads which can cause them to oscillate at excessive magnitudes. Liquid sloshing absorbers can be used to suppress these excessive oscillations for structural control purposes [8, 9] by tuning the frequency of the sloshing to the natural frequency of the structure to be controlled. These absorbers are simple structures consisting of a partially filled container of liquid with a free surface.

Shallow liquid level rectangular sloshing absorbers are the focus of this paper. This is because shallow liquid level sloshing absorbers have been found to be more effective energy dissipaters than deep liquid level absorbers [5, 6]. Rectangular shaped sloshing absorbers have attracted considerable attention in the literature [4, 9, 10]. Earlier work demonstrated the superior energy dissipation efficiency of a rectangular liquid damper through the introduction of an obstruction [7]. A parametric free-vibration study was undertaken giving an increase of up to 60% energy dissipation in the presence of the obstruction. However no analysis was undertaken to experimentally verify the data. Smoothed Particle Hydrodynamics SPH is used in this paper to numerically predict the experimental observations in [7].

Numerical predictions in this study are undertaken using SPH due to its ability to simulate liquids without the need for a mesh structure. A 2-dimensional rectangular sloshing absorber with and without obstructions is modelled here. Due to its Lagrangian nature SPH can accurately capture complex free surface behaviour [1, 2]. SPH has been experimentally verified previously, analysing rectangular sloshing absorbers with attached obstructions [4]. Suggested optimum ratios given in [7] for damper container dimensions, liquid depth and obstruction height and spacing have been analysed here numerically. Displacement histories and liquid velocities are analysed with regards to collision instances and interaction between the liquid, wall and obstructions.

Rectangular Absorber Cases Analysed

Two rectangular absorber cases are analysed in this paper. The first case is a rectangular absorber without obstructions with a container length 370mm and height 125mm. The second case is the same container with two semi-circular obstructions attached to the bottom of the container with a 6mm height located a quarter of the container's length away from each wall. This is the suggested optimum case from [7].

Numerical Model

Smoothed Particle Hydrodynamics (SPH) is a Lagrangian computational modelling tool used to accurately capture complex free surface fluid behaviour. The SPH code used for this paper was developed by the CSIRO Division of Mathematics, Informatics and Statistics. A standard form of the quasi-compressible SPH method is used here [2].

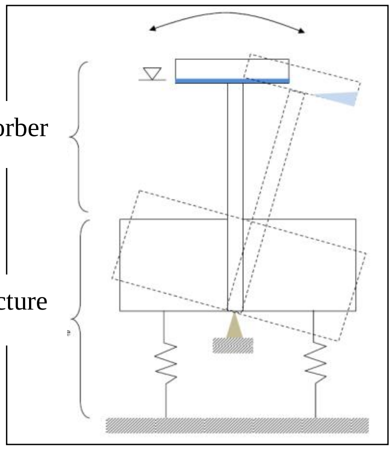

Figure 1. Schematic of the structure with an absorber.

A schematic of the numerical model is displayed in Figure 1. This consists of a mechanical oscillator whose motion is designed to be rotational around a pivot point. A container to accommodate the sloshing liquid is mounted on top. As this structure is excited, the container on top is subjected to angular oscillations similar to [1]. Here the uncontrolled structure has a mass of 16.6kg, an equivalent viscous damping ratio of 0.015 ± 0.002 and inertia of 3.2kg m^2. Water is used as the sloshing liquid with a density of 1000kg m^{-3} and dynamic viscosity of 0.001 Pa s. The free surface length is 370mm and the distance of the obstructions from the centre of the container is 92.5mm. The liquid depth and liquid sloshing frequency for both without and with obstruction cases is 8mm and 0.38Hz respectively. The structural frequency is approximately 0.5Hz. It can be shown that the liquid sloshing frequency is related to liquid depth (h_w) in Eq. (1) from [7]. According to Eq. (1) the sloshing frequency is the same as the structural frequency for a liquid depth of approximately 14mm.

$$h_w = \frac{(2 f_l L)^2}{g} \tag{1}$$

f_l = Liquid sloshing frequency
L = Length of rectangular absorber
g = Gravity

Numerical Predictions

The displacement history of the uncontrolled structure is presented in Figure 2 with a 16° initial displacement. The structure has light damping characteristics with a damping ratio of approximately 1.5%. Transient displacement histories without (dashed line) and with (solid line) two semi-circular obstructions, (obstruction height of 6mm) and liquid depth of 14mm are displayed in Figure 3. This tuned case is quite effective due to having a natural structural frequency equal to the liquid sloshing frequency of approximately 0.5 Hz.

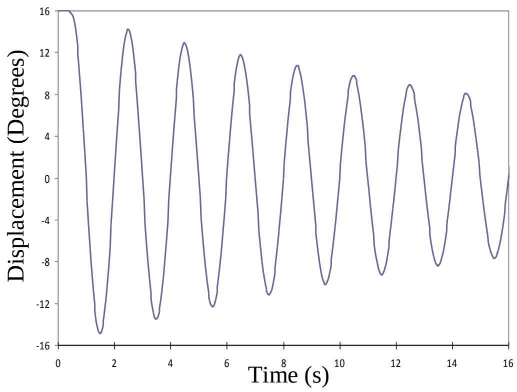

Figure 2: Displacement history of uncontrolled structure.

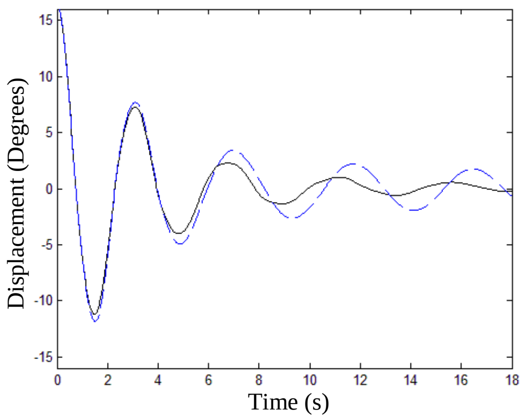

Figure 3. Displacement histories of rectangular absorber without (------) and with (——) two semi-circular obstructions with obstruction height 6mm and liquid depth of 14mm.

Transient displacement histories without (dashed line) and with (solid line) two semi-circular obstructions, (obstruction height of 6mm) and liquid depth of 8mm are displayed in Figure 4. The absorber without obstructions has a damping factor, ζ as defined in Eq. (2) of 0.1 The absorber with obstructions is more effective than the absorber without obstructions, with a damping factor of 0.135 being 26% more efficient. This case is more effective than the tuned 14mm liquid depth case as the tuned case's period of oscillations are longer due to the larger liquid depth and therefore the amount of time for the structure to cease oscillating is increased. The duration of in phase oscillations, that occur when the liquid and the structure become in phase with each other, is longer for the tuned case. This occurs after approximately 8s in Figure 3 as the sloshing from the larger liquid depth forces the structure to continue oscillating in phase with the liquid also increasing the amount of time to cease oscillating.

$$\zeta = \frac{1}{2\pi n} \ln\left(\frac{A_0}{A_n}\right) \tag{2}$$

n = Number of vibration cycles
A_0 = Initial vibration amplitude
A_n = Amplitude of vibration after n cycles

The obstructions become most effective after approximately 10 seconds in Figure 4 where they eliminate the small in phase oscillations. The obstructions eliminate the in phase oscillations due to the shear energy dissipation occurring during wave to obstruction interactions reducing the velocity of the fluid. This reduction in velocity pushes the travelling wave out of phase with the structure. The increased energy dissipation results in the structural oscillation to stop in approximately half the time as compared to the case of the absorber without obstructions.

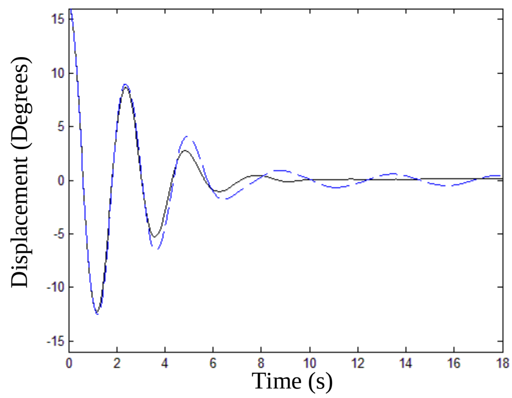

Figure 4. Displacement histories of rectangular absorber without (------) and with (——) two semi-circular obstructions with obstruction height 6mm and liquid depth of 8mm.

In Figure 5, snapshots of velocity are presented during the first three cycles of oscillation of the rectangular container without obstructions (odd columns) and with two obstructions (even columns) for 8mm liquid depth. Four instances are shown for each cycle, roughly corresponding to the positive peak displacement, zero displacement, negative peak and back to zero. The first cycle of oscillation is from 0.1s to 1.8s, the second cycle from 2.4s to 4.3s and the third cycle from 4.9s to 7.1s. In these frames blue indicates 0 m/s and red is 1 m/s for the liquid velocity.

Maximum energy dissipation is achieved when the wave to wall interaction occurs at zero structural displacement and the liquid and structure are travelling in opposing directions. This is due to the structure having maximum velocity at zero displacement. Minimum momentum opposition is achieved when the wave to wall interaction occurs at zero structural displacement and the liquid and structure are travelling in the same direction. The first wave to wall interaction occurs at 1.1s at negative peak displacement displayed in Figure 5. For the absorber with obstructions the liquid is forced to jump over the obstruction delaying the wave to wall interaction compared to the absorber without obstructions. The beginning of the wave to wall interaction occurs at approximately 0.8s. At 0.8s in Figure 4 the structure is still yet to reach negative peak displacement. As the liquid and structure are still travelling in the same direction maximum energy dissipation is not achieved.

The velocity profile comparison at 1.8s in the even column shows that the obstruction increases the velocity of the travelling wave as it passes over the obstruction from left to right. This is in direct agreement with [7] in that the liquid is accelerated while flowing past an obstruction.

The second cycle of oscillation (in Figure 4) displays the reduction of the structure's displacement by introducing the obstructions. The wave to wall interactions are displayed in Figure 5 at 3.7s for negative peak displacement and 4.9s for positive peak displacement. While the liquid travels from left to right in the absorber after the left wave to wall interaction (negative peak displacement) the liquid velocity increases as it travels over the left obstruction. However the right obstruction reduces the liquid's velocity as the liquid travels over the obstruction from left to right delaying the right wave to wall interaction. As a result, the wave to wall interaction occurs approximately 0.15s later than the absorber without obstructions. Therefore the beginning of the wave to wall interaction occurs at approximately 4.66s (at positive peak displacement) in Figure 4, disrupting the oscillations of the structure. Maximum energy dissipation (at zero displacement) cannot be achieved as the structure's motion pushes the liquid in the direction the structure oscillates. However the obstructions delay the wave to wall interaction enough to occur at positive peak displacement and not while the liquid and the structure are travelling in the same direction. This is an advantage as energy dissipation is significantly increased when the wave to wall interaction occurs at peak displacement (zero structural velocity) or when liquid and structure are travelling in opposite directions as opposed to the same direction.

The beginning of the wave to wall interaction of the absorber without obstructions occurs at approximately 4.5s where the structure is travelling towards maximum displacement in Figure 4. As both liquid and structure are travelling in the same direction less energy is dissipated compared to the absorber with obstructions.

Conclusions

SPH was used to experimentally validate earlier work of a rectangular liquid damper with the introduction of obstructions. Suggested optimum ratios were given for damper container dimensions, liquid depth and obstruction height and spacing. An absorber without and with two obstructions were analysed for displacement history for both 14mm (tuned) and 8mm liquid depths. Snapshots of velocity contours for the first three cycles of oscillation were also analysed without and with two obstructions for 8mm liquid depth. The 8mm liquid depth cases are more effective than the tuned 14mm liquid depth cases as the tuned case's period of oscillations and amount of in phase oscillations are longer due to the larger liquid depth and therefore the amount of time for the structure to cease oscillating is increased. Introducing obstructions to a rectangular absorber using suggested ratios from [7] improves its efficiency significantly through increased energy dissipation by eliminating the structural oscillations in approximately half the time and increasing viscous damping ratios by 26% as compared to the case of the absorber without obstructions.

Acknowledgments

It is gratefully acknowledged that J.A. Grant is supported by CSIRO and Victoria University Postgraduate Scholarships during the course of this work.

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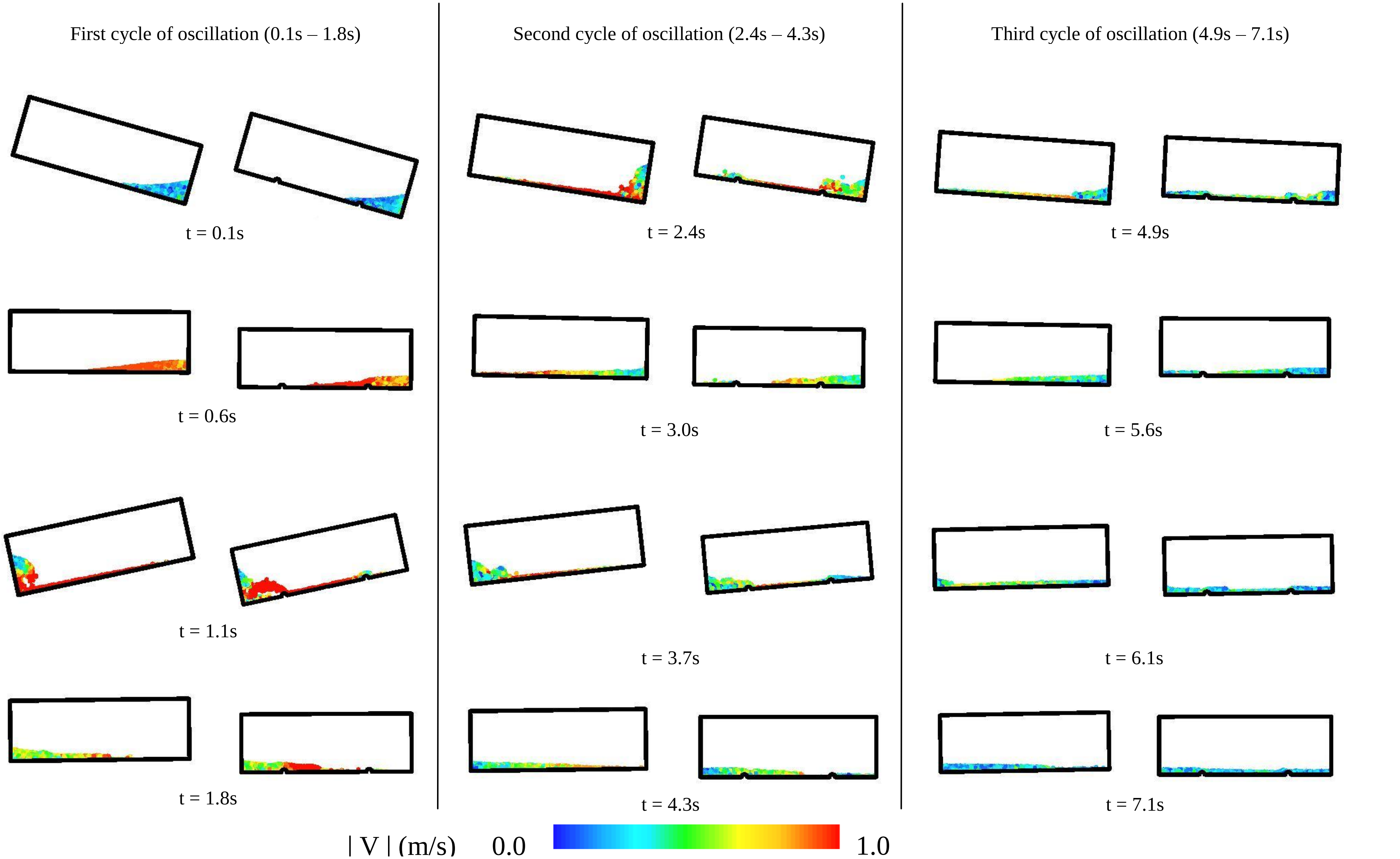

Figure 5. Snapshots of the velocity contours at particular marked instances during the first 3 cycles for 8mm liquid depth. Odd columns correspond to the no obstruction case, even columns correspond to the suggested enhanced design with two semi-circular obstructions of height 6mm. Velocity scale runs from 0 m/s to 1.0 m/s.