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Control of Liquid Sloshing in Flexible Containers: Part 2. Top Straps

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Abstract

As described in Part 1, sloshing is the low frequency periodic motion of the free surface of a liquid in a partially filled container. The dynamic response of structures containing liquid can be significantly influenced by these low frequency oscillations, and interaction with the sloshing liquid could lead to instabilities. The authors' earlier work indicates that container flexibility can be effective in sloshing control. In Part 2, the added advantage of top straps is discussed towards a more practical optimal container design.

Introduction

Liquid in an open container can move back and forth across the basin in standing (or travelling) waves at discrete natural frequencies, as described in Part 1. This low frequency oscillation of the liquid is defined as sloshing. In Part 2 of this two-part paper, the effect of horizontal straps is investigated in controlling liquid sloshing in a flexible container. A schematic view of such a container is shown in Figure 1. As further illustrated below, a flexible container with straps on top, is chosen as a practical way to implement tuning with added masses without excessive wall deflection. Straps on top of a flexible container, reduce static deflection due to the addition of liquid and point masses.

Liquid sloshing and its control have attracted attention in engineering research due to the consequences of uncontrolled sloshing. Welt and Modi [9] showed that the sloshing resulting from external forces is often critical when the excitation frequency is near the liquid natural frequency. The methods of determining natural frequencies and mode shapes of such flexible structures could be found in the works of Kana and Abramson [7], Chen and Haroun [3] and Jeong and Kim [6]. Further investigations on using structural flexibility for the control of liquid sloshing using finite element analysis are reported by Anderson [1] and Gradinscak et al. [4, 5].

Numerical Model

The container used for this part of the study, is identical to that described in Part 1. It has a rectangular shape, 1.6 m in length, 0.4 m in width and 0.4 m in high. The wall thickness is 1 mm. The material properties for aluminum are used for the container. As in Part 1, the ANSYS FEA [2] program has been used to create the numerical model of the flexible container and liquid using finite elements, simulate liquid sloshing in the container and obtain displacement values at different nodes for the container and liquid.

The container is modelled with two-dimensional rectangular shell elements. Such an element has constant thickness, and it is defined by four nodes, with six degrees of freedom at each node. 1% critical damping is applied to the structure without liquid. In addition, three link elements are attached at the top of the container at three points as straps. A link element is defined by two nodes, the cross-sectional area and material properties. The material properties for aluminum are used also for the link elements. The numerical model is illustrated in Figure 1 with the top straps.

Three dimensional brick finite elements are used to model the liquid. This element is defined by eight nodes having three degrees of freedom at each node. The parameters are chosen for a homogeneous, inviscid, irrotational and incompressible liquid. The material properties for the liquid are defined by the fluid elastic modulus and the density. The liquid depth is 0.3m. The liquid is kept undamped throughout the simulations.

Two structural mass elements are added to each long side of the container, on either side of the middle strap, in order to tune the natural frequency of the container with that of the fundamental sloshing mode. A structural mass element is defined as a single node that has a concentrated mass acting along the element's own coordinate directions.

Fluid-structure interaction is achieved by coupling the liquid displacement with that of the container walls in the direction normal to the walls. The container and liquid parameters are adjusted to ensure that the frequency of the structure and liquid are close numerically to guarantee strong interaction. Eigenvalue analysis is used to determine natural frequencies and mode shapes, and direct numerical simulation is used to determine the displacement histories of the liquid and container.

The disturbance used is the same as in Part 1. Sloshing is induced by imposing a transient sinusoidal displacement of one cycle to the base of the container in the X direction, as defined in Figure 2 of Part 1. The peak-to-peak base displacement is 0.01 m with frequency of 1.34 Hz. This frequency corresponds to the theoretical sloshing frequency of a rigid container of the same dimensions [8].

As described in Part 1, simulations were performed previously for 40 seconds, by allowing the container time for the first 20 seconds to assume its static equilibrium, and then, by imposing to the base a transient disturbance along the X axis. Two sample results are presented in Figure 2 for 40-second simulations. In Figure 2(a), the container and liquid free surface displacement histories are presented for the case of 9-kg total added mass without top straps. In Figure 2(b), the histories are given for the 9-kg added mass case with top straps. In both of these figures, the right column represents the liquid sloshing history, obtained as the difference between the vertical displacements of the top middle liquid nodes, as defined in Part 1. During the first 20 seconds, the liquid surface simply bobs up–and-down with an amplitude comparable to that of the container displacement. With the 40-second runs, liquid sloshing starts only after the transient base disturbance is applied at the twentieth second. As described in Part 1, when the liquid sloshing amplitude is compared with 20-second simulations with disturbance applied at the start, similar out-of-phase liquid sloshing histories are obtained, indicating that 40-second simulations with a settling down period, are not needed. Therefore, the rest of the results presented here are from 20-second simulations.

Results and Discussion

From a comparison between the static container displacements with and without straps within the first 20 seconds, the practical significance of top straps can be observed. As described in Part 1, added mass is needed to tune the container flexibility to liquid sloshing for optimal control. As indicated in Figure 2(a), with a 9-kg added mass, a static deflection of about 6 cm occurs in the container. With the addition of three straps at the top, the static deflection reduces to about 1 cm.

It is known that the sloshing due to external forces becomes critical when the excitation frequency is close to the fluid sloshing frequency [1]. Ideally, to control sloshing, the objective is to tune the container natural frequency to the exact sloshing frequency. As described in Part 1, tuning is achieved by attaching different amounts of mass to the container to decrease its natural frequency, while keeping all other parameters the same. Tuning for the cases presented in this paper has been achieved by adding structural mass elements at two points on either side of the middle strap, as described in the previous section. The presence of significant energy transfer between the liquid and container is considered to be a sign of appropriate tuning. Such energy transfer is detected by a beat in the displacement history of the container walls or liquid.

As shown in Figure 3(a) of Part 1, for the rigid container (with no added mass and no straps), the sloshing amplitude does not decay, after the excitation is applied for the first 0.74 seconds. As in Part 1, this case is taken as the comparison base here for the flexible wall cases with and without additional elements to demonstrate the effectiveness of sloshing control.

In Part 1, the best tuning case is shown to be around an added mass of 7 to 8 kg without straps. With straps, a series of numerical trials has been conducted to determine the most promising case. In Figure 3, the histories are presented for selected cases of the horizontal oscillations of the top middle nodes of the long container walls, and the vertical oscillations of the corresponding liquid nodes. Figures 3(a) to 3(e) correspond to cases of 0, 6 kg, 10 kg, 14 kg and 18 kg added mass, all with three top straps. The right column in each figure is the corresponding sloshing history, calculated as the difference between the vertical displacements of the two liquid nodes at the top middle of the long sides of the container.

From a comparison of Figures 3(a) to 3(e), it is seen that with added masses of 6 kg and 10 kg, the peak sloshing amplitude drops significantly with respect to the no added mass case and the case of the rigid container. The best result is obtained for the 10-kg added mass case. By adding masses of 14 kg or more, the tuning effect is lost, and the liquid sloshing amplitude starts to increase.

In Figure 4, the rms liquid sloshing amplitudes of different cases are shown as a function of added mass for all the cases presented in Parts 1 and 2. The rms amplitudes are normalized by the rms sloshing amplitude in the rigid container. This figure is obtained by adding the strapped cases to Figure 5 of Part 1. As seen in this figure, the optimal control achieved with straps corresponds to a decrease in the sloshing amplitude of about 80 % between 6 to 10 kg added mass. Similar to the cases of sloshing control without straps, but only with added mass, the control is more sensitive for smaller added mass cases than for larger ones, as indicated by the steeper slope to the left of the best control.

Conclusion

The effect of additional elements, along with container flexibility, in sloshing control is presented. The results from these simulations have shown that the sloshing amplitude is significantly lower in comparison with the rigid container case. With three straps on top and for the dimensions chosen here, the best suppression is obtained for the 6 to 10-kg added mass on the flexible container.

The fluid-structure interaction model presented here is based on numerical modelling. The model allows for an unlimited number of parameters to be examined, so that a comprehensive investigation of various elements used for sloshing suppression can be undertaken. The results presented require experimental verification, and this work is currently underway.

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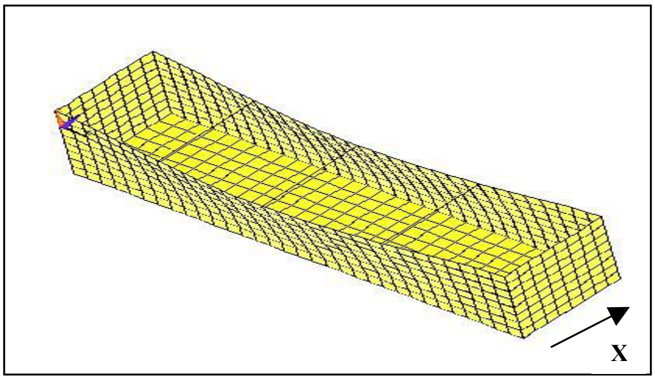

Figure 1. The first mode shape of the flexible container without water, showing the locations of the three straps.

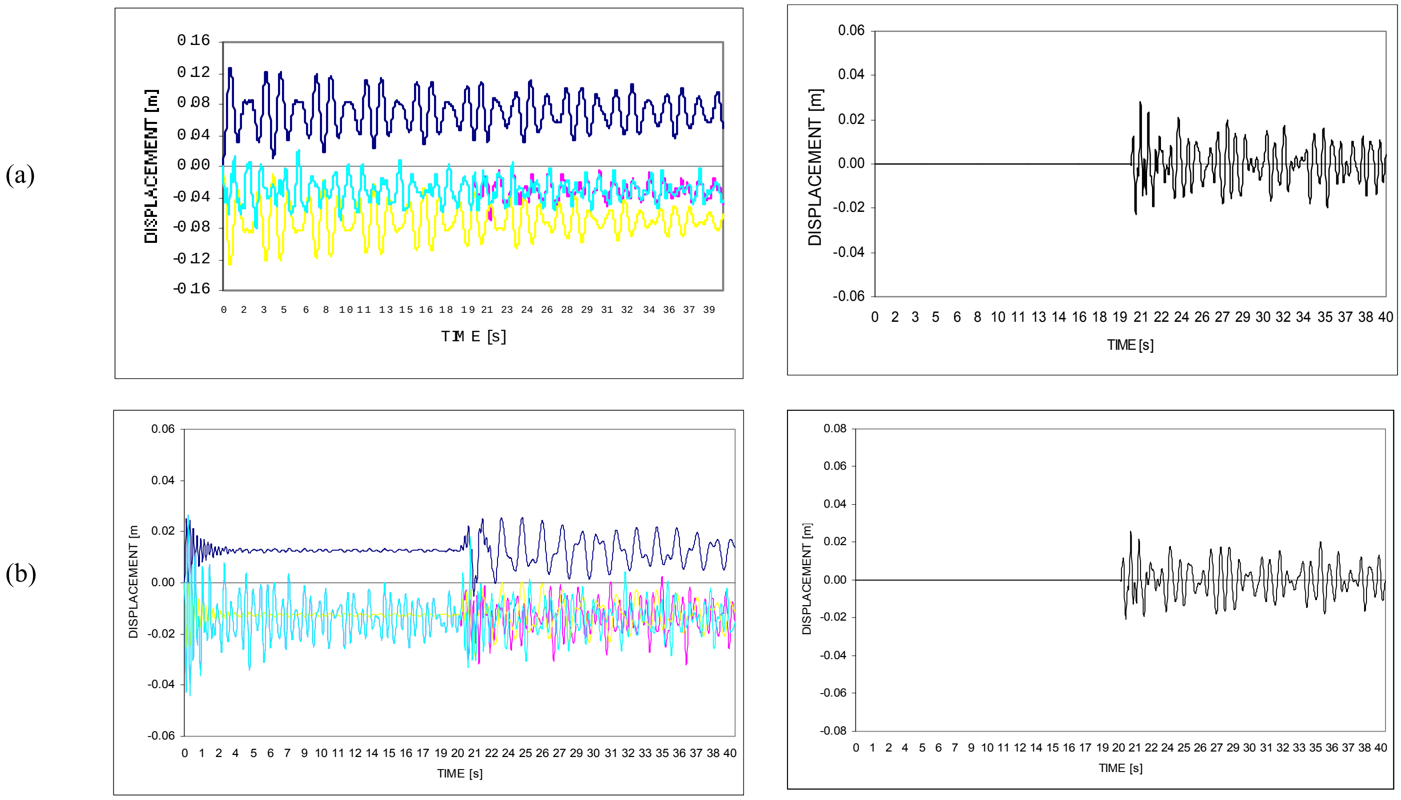

Figure 2. Selected 40-second simulations. (a) 9-kg added mass without straps. (b) 10-kg added mass with straps. Left column, displacement (top and bottom, horizontal displacement of the two sides of the structure; two in the middle, vertical displacement of the adjacent liquid nodes); and right column, sloshing histories.

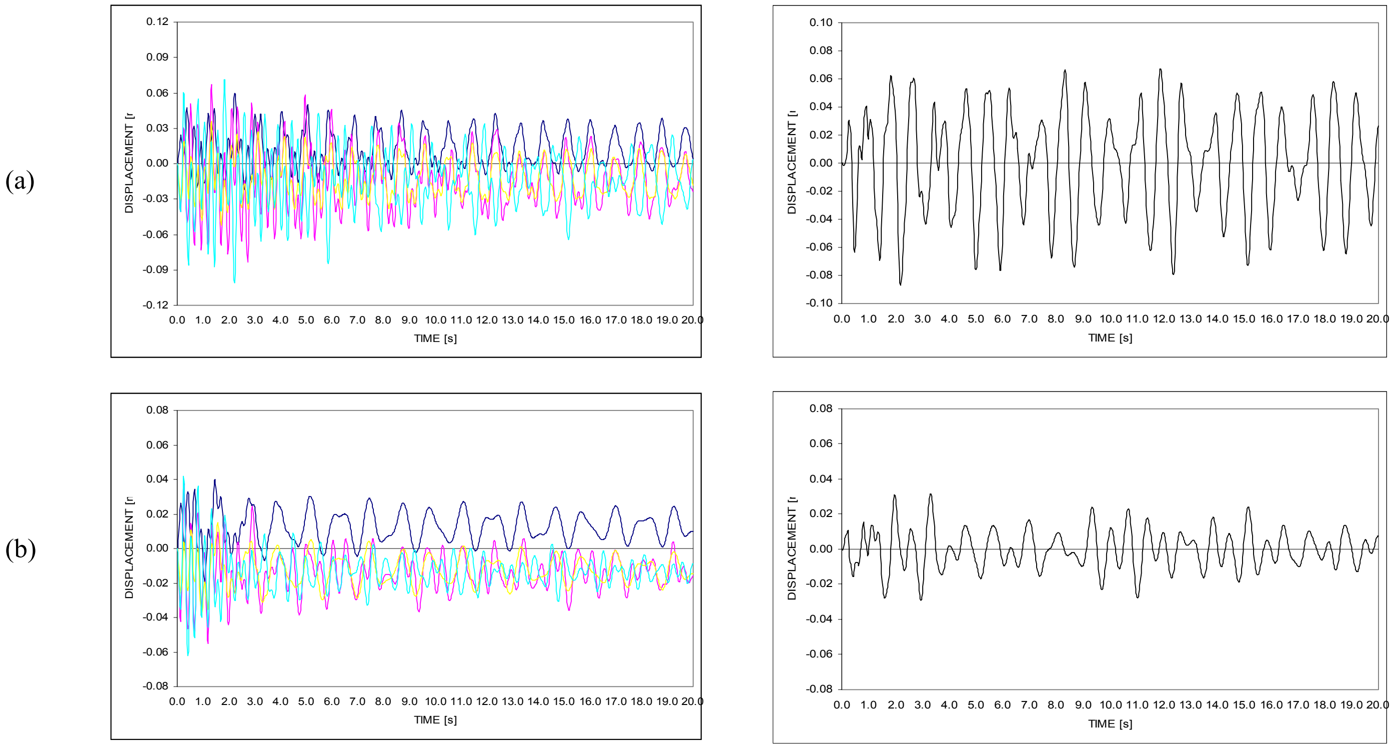

Figure 3. Strapped cases. (a) no mass; added masses of (b) 6 kg; (c) 10 kg; (d) 14 kg; (e) 18 kg.

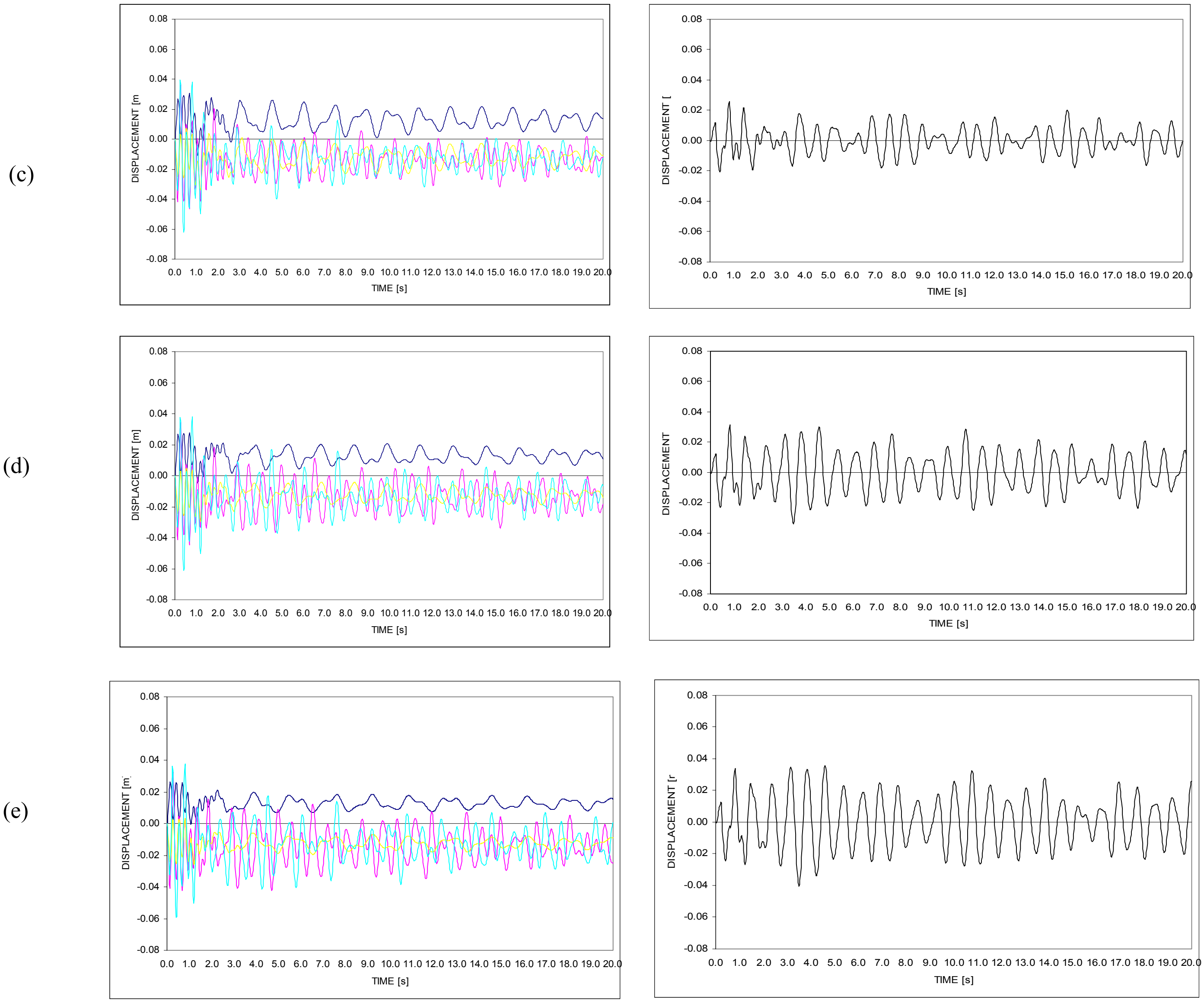

Figure 3. Continued.

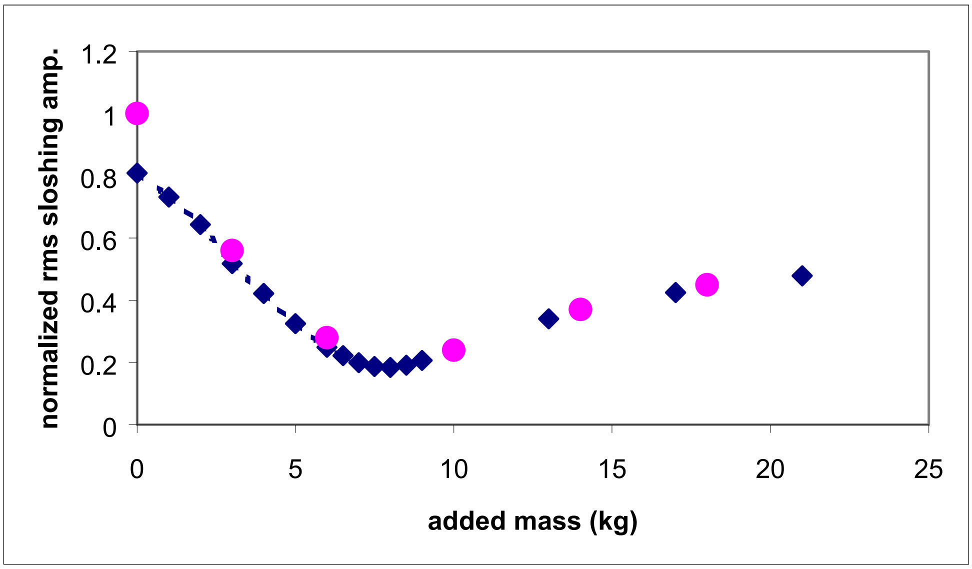

Figure 4. Variation of rms sloshing amplitude with added mass for cases without (◆) and with (●) straps.