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# LIQUID SLOSHING IN FLEXIBLE CONTAINERS, PART 1: TUNING CONTAINER FLEXIBILITY FOR SLOSHING CONTROL

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## ABSTRACT

Sloshing is the low frequency oscillation of a liquid in a partially filled container. Amongst the rather limited attempts in the literature to suppress sloshing, no other work exists to employ the flexibility of liquid containers for control purposes. In this paper, earlier efforts are summarized to numerically predict the tuning which must exist for effective control. In addition, simple experiments are reported to verify the presence of numerically predicted tuning condition.

## INTRODUCTION

Sloshing of large liquid masses has been a major factor in engineering design in which the stability of structures is of main concern. If not controlled effectively, these low-frequency oscillations may cause loss of stability during transport or structural damage in storage containers. The detrimental effects are mainly due to induced dynamic forces and the shifts of the centre of gravity of the moving liquid. If the containment structure is flexible, the liquid–structure interaction problem becomes even more complex as compared to the case of a rigid container. The complexity with the flexible containers is the result of moving liquid boundaries. Hence, the dynamic response of a flexible container filled with liquid may have characteristics significantly different from those with rigid walls.

Early research can be found on the use of flexible containers in Chen and Haroun (1994) and Jeong and Kim (1998). These works reported investigations on container flexibility with a primary interest to determine natural frequencies and mode shapes of containers with liquid.

Anderson (2000) investigated, for the first time, the possibility of using container flexibility for the control of liquid sloshing. Gradinscak et al. (2001 and 2002) investigated the design of flexible containers and observed significant reduction of sloshing amplitudes when the container natural frequency is tuned to the liquid sloshing frequency. The effect of container flexibility using numerical predictions was also reported by Güzel et al (2005). Garrido (2003) considered a parallelepiped container partially filled with liquid. This container was accelerated by a constant driving force, and then decelerated due to frictional forces. A simple mechanical model of the sloshing liquid as a pendulum, was developed to define the interaction between the sloshing liquid and its structure. Results obtained from this model and experiments were reported as satisfactory while acknowledging the simplicity of the model. Mitra and Sinhamahapatra (2005) developed a new pressure based Galerkin finite element code that could handle flexible walls. The analyses were restricted to linear problems and only small amplitude waves.

This paper presents the research outcome to date, on the possibilities of using a container with flexible walls to achieve control of liquid sloshing when the container walls interact with the liquid. To this end, numerical predictions, obtained with a commercial finite elements package, and experimental observations are discussed. The second part of the subject matter is presented in an accompanying paper where the possibility of structural vibration control is investigated using intentional liquid sloshing, Gradinscak et al. (2006)

## NUMERICAL MODEL AND PROCEDURE

The container used for the numerical model was made of aluminium, an open top rectangular prism of 1.6 m in length, 0.4 m in width and 0.4 m in height. The wall thickness was 1 mm. The container was filled with water to a depth of 0.3 m. ANSYS (2002) finite element analysis package has been used to create the numerical model of the flexible container and the sloshing liquid. The objective of the simulations was to obtain the displacement histories at several locations of the container and liquid.

The container was modelled with two-dimensional rectangular shell elements. 1% equivalent viscous damping was assumed for the structure without liquid. Three dimensional brick elements were used to model the inviscid and incompressible liquid. Fluid-structure interaction was achieved by coupling the liquid displacement with that of the container walls in the direction normal to the walls. Sloshing was induced by imposing a transient 5 mm-sinusoidal displacement of one cycle to the base of the container in Y-direction, as shown in Figure 1. The frequency of this disturbance was chosen to be 1.34 Hz, the fundamental sloshing frequency of a rigid container of the same dimensions.

The concept of using a flexible container to control sloshing of a liquid is similar to that of using a tuned absorber to control excessive vibrations of a mechanical oscillator. For a tuned absorber, the natural frequency of the absorber is tuned to that of the structure to be controlled to maintain minimum oscillation amplitudes, while the absorber is put in resonance intentionally. Here, the sloshing liquid is taken to be analogous to the structure to be controlled, whereas the flexible container is expected to act like the tuned absorber. Tuning the container dynamics to that of the sloshing liquid is attempted by adding point masses on the flexible container. Two masses are added directly above the "observed container node" indicated in Figure 1, on the free edge of the flexible walls.

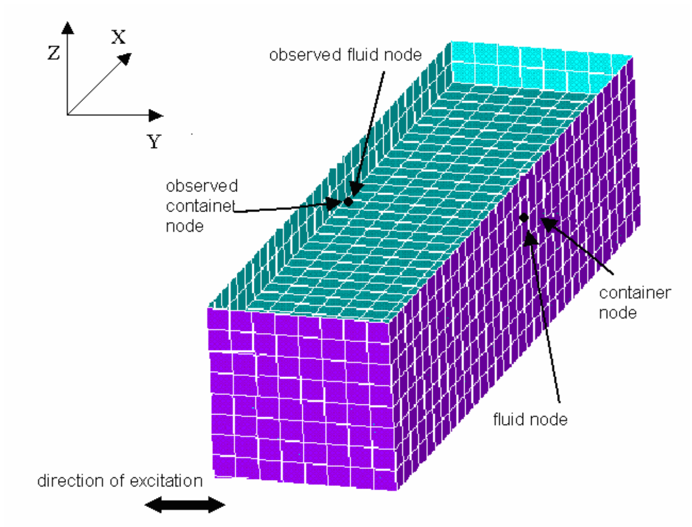



**Figure 1**. The numerical model and the location of the observed nodes. The container has the dimensions of 1.6 m x 0.4 m x 0.4 m.

## NUMERICAL PREDICTIONS

The vertical displacement histories of the two observed fluid nodes (indicated in Figure 1) are given for the **rigid container** in the left column of Figure 2a. These two histories are 180 degrees out of phase, indicating that when the liquid climbs at one wall, it drops at the other one. At the completion of one period of excitation, the liquid climbs approximately 20 mm on one wall, and it comes down by about 20 mm on the opposite wall. As there is no viscous dissipation, liquid sloshing continues with almost constant amplitude. The resulting sloshing amplitude for the rigid container is around 40 mm, and it is shown in the right column in Figure 2a. Sloshing history on the right, is given as the difference of the vertical displacements of the two liquid nodes shown in Figure 1.

In Figure 3a where the corresponding frequency spectrum of the sloshing history in Figure 2a is given, the fundamental sloshing frequency is suggested to be around 1.4 Hz, quite close to theoretical fundamental frequency of 1.34 Hz. Another small spectral peak is apparent, around 2.3 Hz, indicating the second sloshing frequency.

The displacement history for the flexible container with no added mass and for 3-kg, 5-kg, 9-kg 11-kg and 13-kg added mass are presented in Figures 2b, 2c, 2d, 2e, 2f and 2g, respectively, in the left column. The horizontal displacement histories of the container nodes are the top and the bottom ones. The vertical displacement histories of the liquid surface nodes are indicated with two middle lines, with smaller displacement magnitudes than those of the container.

There is an apparent decrease in the frequency of the displacement histories with increasing mass. Also, the container walls deflect substantially after filling the flexible container with water. There is no significant change in this level of deflection as increasing masses are added to tune the container. This last observation indicates that the weight of the water is more significant to deflect the container walls than that of the added mass.

The sloshing histories for the flexible container with no added mass and for 3-kg, 5-kg, 9-kg 11-kg and 13-kg added mass are presented in Figures 2b, 2c, 2d, 2e, 2f and 2g, respectively, in the right column. The sloshing amplitude for the container with no added mass is around 60 mm, larger than that of the rigid container. The gradual decay of the envelope of oscillations, is due to 1% critical damping of the structure. With 3-kg added mass, an improvement is apparent. The sloshing amplitude decreases below 40 mm in the beginning, to around 25 mm at the end simulations. With 5-kg added mass sloshing amplitude decreases below 20 mm. The best tuned case is with 9-kg added mass and with sloshing amplitude at the end of simulation of smaller than 10 mm. With 11-kg and 13-kg masses, tuning is gradually lost and sloshing amplitude starts to grow again.

As discussed briefly earlier, the suppression effect is the result of tuning the frequency of the flexible container to that of the sloshing liquid. The suppression is the result of this tuning as tuning dictates the timing of a sloshing wave and the corresponding structural oscillations of the flexible container. Presence of flexibility of the container complicates the tuning process, as changing the container parameters affects the dynamics of the overall structure, including the fundamental frequency of sloshing.

As mentioned earlier, frequency spectra of the same cases are given in Figure 3, for both the structural and sloshing oscillations. For the no-mass case in Figure 3b, the spectral distribution is rather crowded with structural peaks at 0.7 Hz, 1.2 Hz, 1.7 Hz, 2.3 Hz and 2.7 Hz. Sloshing also has a spectral peak at 1.2 Hz, possibly driving the lighter container at this frequency. In addition, the same two spectral peaks as in the rigid container case are clearly noticeable. This last trend is not surprising, considering that the flexible container is clearly off-tuned for this particular case.

With 3-kg added mass, the spectral distributions of both the container and the sloshing liquid are significantly simplified, as compared to the case with no added mass, being practically limited to below 2 Hz. The container has spectral peaks at approximately 0.75 Hz, 1 Hz and 1.4 Hz. Sloshing has spectral peaks at 1 Hz and 1.4 Hz. Clearly, the second sloshing peak coincides with that of the rigid container at this frequency. The liquid driven oscillations at 1.2 Hz from the no-added-mass case, now appear to be around 1 Hz.

With 5-kg added mass, structure has two dominant spectral peaks around 0.8 Hz and 1.2 Hz. In addition, both the structure and the liquid have a common frequency at approximately 0.9 Hz. The spectral peak magnitudes of the structure are significantly larger than those of the liquid, possibly indicating that the structure may now affect the response of the liquid more than being affected by it. The control effect of the structure is suggested quite clearly at its second spectral peak where the sloshing magnitudes are suppressed significantly.

With 9-kg added mass, magnitudes of the structural peaks dominate those of sloshing. Structure still has only two peaks. An interesting observation is that the magnitude of the second spectral peak at 1 Hz is now smaller than the magnitude of the first peak at 0.7 Hz. The tuning effect implied for the 5-kg case is now much clearer at 1 Hz where the structure has a peak, and the liquid has practically no response.

With 11-kg and 13-kg added mass, sloshing around 1.4 Hz becomes significant again, indicating that the interaction between the structure and liquid is being lost. The result of this loss is the appearance of independent spectral peaks for both the structure and liquid separately. As expected, with larger values of added mass, spectral peaks consistently show up at lower frequencies for the structure.

A summary of the numerically predicted tuning process is presented in Figure 4 with the root-mean-square averages of sloshing amplitude. The minimum sloshing amplitude is for about 7 to 9-kg added mass on the flexible container, corresponding to better then 80% attenuation as compared to that in the rigid container. Considering the respective slopes of the trend line on either side of the best case, the control effect is more sensitive as the tuning is approached from the left. Therefore, it may be advantageous to be to the right of the best performance where the added mass can be somewhat larger than the optimal without significant loss of effectiveness.

## EXPERIMENTS

Simple experimental observations are reported in this section. It must be emphasized here that the experimental verification of the detailed dynamic response is an on-going effort presently. What is presented here is only of a qualitative nature as an attempt to validate the presence of "tuning" claimed in the preceding section.

The experimental setup is shown schematically in Figure 5. It consists of a personal computer (1), Techron 7560 power amplifier (2), VTS500, model VG 600-3, electromagnetic exciter (3) and the container mounted on a trolley with a rigid platform (4). The container was identical to the one used for the numerical model. The moving table of the shaker was programmed to provide the required displacement history. This feature was particularly useful to repeat the same transient disturbance as in numerical predictions.

Point masses were added to the flexible container walls, at the same location as in the numerical model, in order to vary the modal frequencies of the container. The purpose of these preliminary tests was to check the magnitude and the distribution of the liquid displacement inside the container. To this end, the container was excited in an identical manner to that of the numerical displacements described earlier.

A transient sinusoidal displacement at the sloshing frequency of the rigid container (1.34 Hz) was given to the container's base. The liquid motion was observed visually by placing rulers on the inside vertical walls of the container, at the free liquid surface. The reported results are within ± 0.5-mm accuracy which was assumed to be quite acceptable at this preliminary stage. In addition, at least three repetitions were used to ensure the repeatability of the reported observations.

The experimental observations are presented collectively in Figure 6, in the same format as the numerical predictions in Figure 4. In Figure 6, the added mass is given along the horizontal axis, whereas the vertical axis represents the peak displacement of the free liquid surface. This point is the same as the one reported in numerical predictions, at the container wall, in the middle of the long side.

The peak displacement of the free surface with no added mass, is approximately 58 mm. The rigid container case is marked with a solid horizontal line to provide the reference. As expected from numerical predictions, as the mass increases, the displacement of the free surface becomes smaller. The displacement is 30 mm with 3 kg, and 18 mm with 7 kg. The change from 7 kg to 9 kg is quite marginal with approximately 70% reduction as compared to the rigid container case. After 9 kg, the change is more noticeable, but it is more gradual than the change to the left of the 7-kg case. With these observations, it is assumed that the numerical predictions of the first part of this paper have practical merit, indicating the presence of "tuning" for effective suppression of the free surface.

Finally, it is worth noting that both the distribution of the free surface displacements around the container walls and symmetry on both sides were checked, and confirmed to agree with the numerical predictions. It should be emphasized that the confirmation claimed here is that of the relative distribution, and not in absolute sense.

## CONCLUSIONS

Numerical predictions obtained with extensive case studies indicate the possibility of employing container flexibility in reducing liquid sloshing. These attenuations are predicted to be in the order of 80% in the rms sense, as compared to a container with rigid walls. Observations from simple experiments indicate the presence of the predicted tuning effect qualitatively.

The presented numerical predictions correspond to a standard finite elements approximation. Although it is the authors' belief that the numerically predicted tuning does exist, detailed experimental verification is still required. Current efforts are to provide such information.

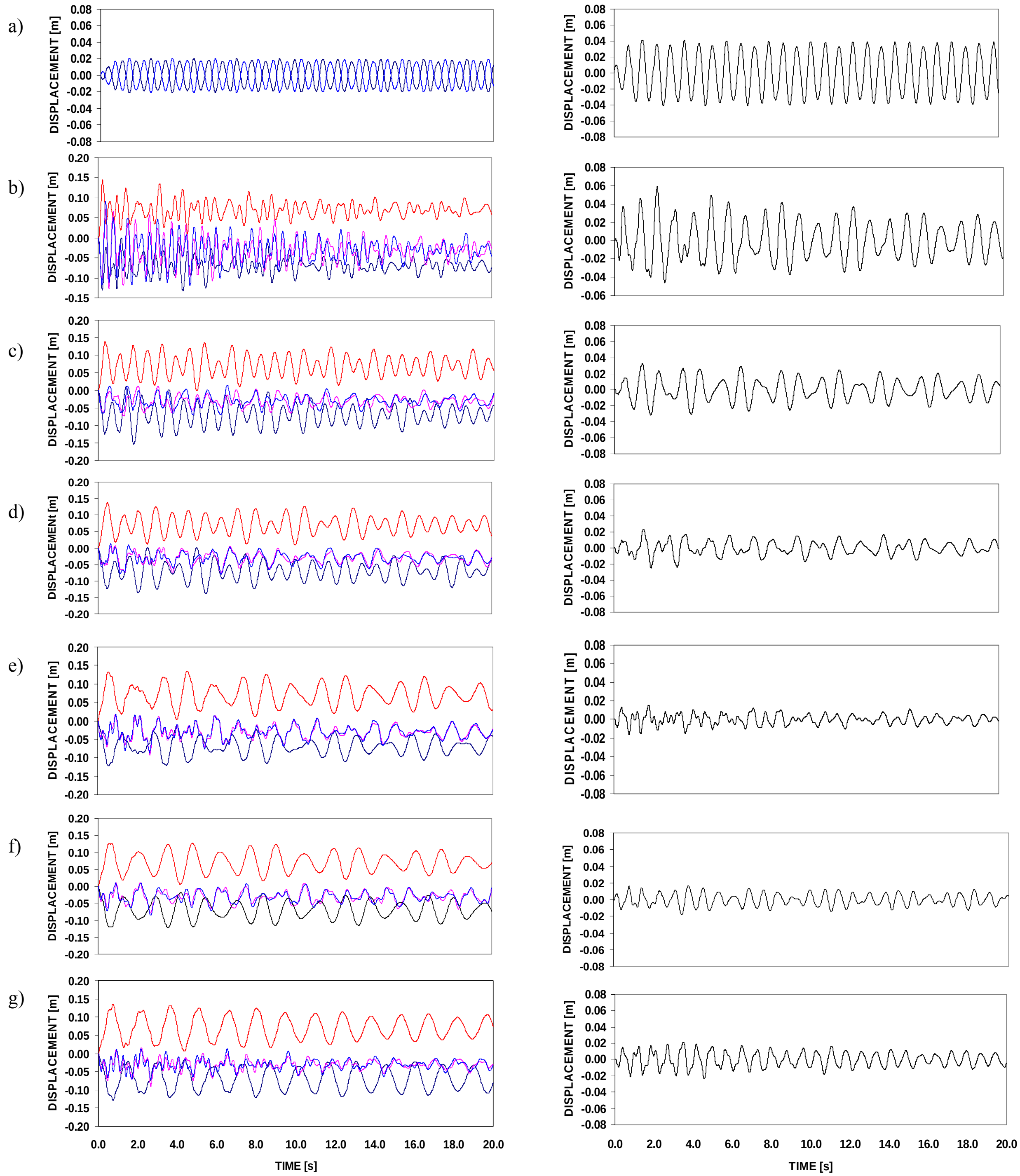
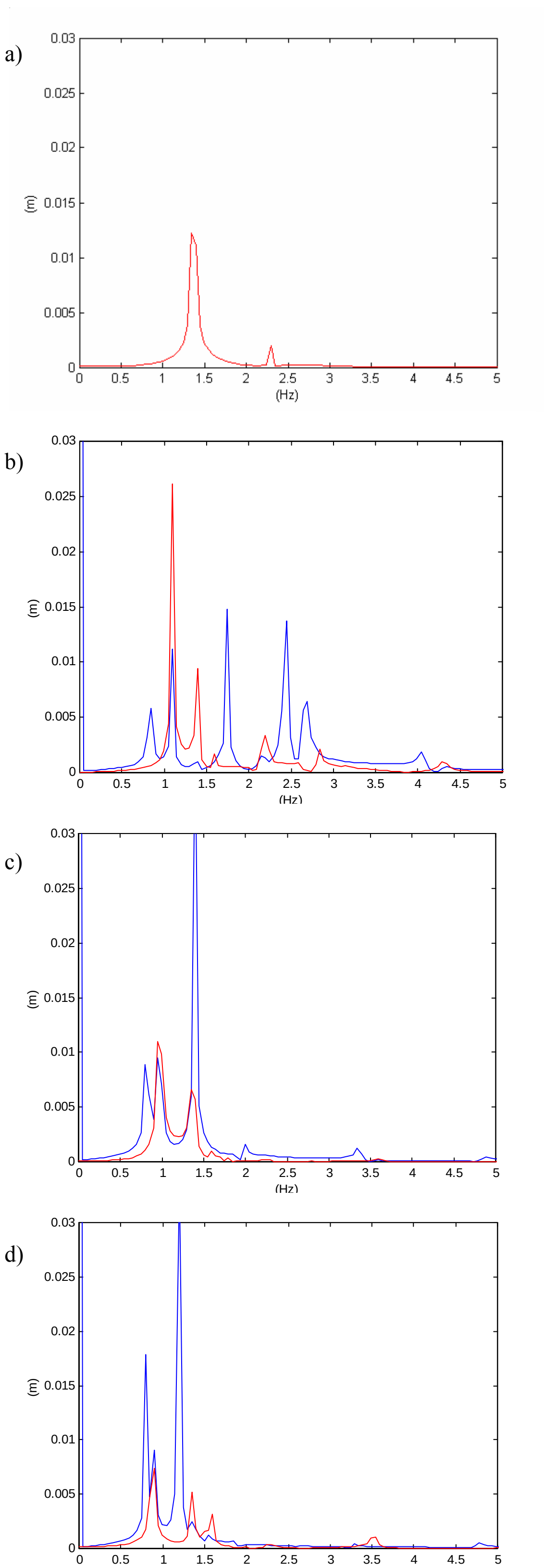



**Figure 2**. Displacement histories of two container nodes (dark blue and red) and two free surface nodes (light blue and magenta) (left column), and of liquid sloshing (right column). a) The rigid container, and flexible containers with added masses of b) 0 kg, c) 3 kg, d)5 kg, e) 9kg, f) 11 kg and g) 13 kg. Displacements are observed at the marked locations in Figure 1.



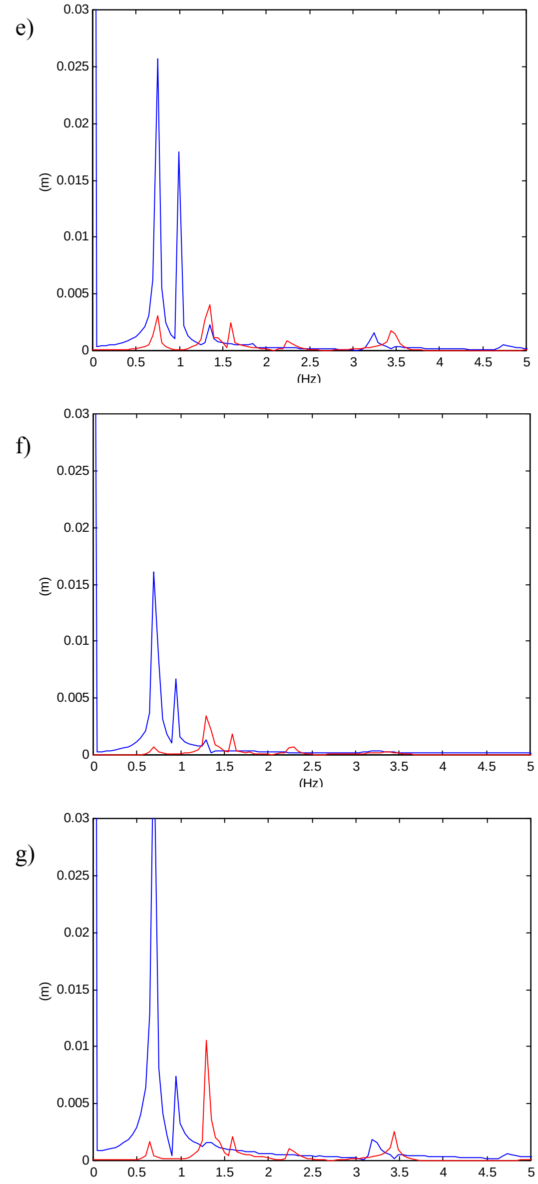




**Figure 3**. Corresponding displacement frequency spectrum of the sloshing liquid (red) and the structure (blue) of the same cases as in Figure 2. a) The rigid container, and flexible containers with added masses of b) 0 kg, c) 3 kg, d) 5 kg, e) 9 kg, f) 11 kg and g) 13 kg.

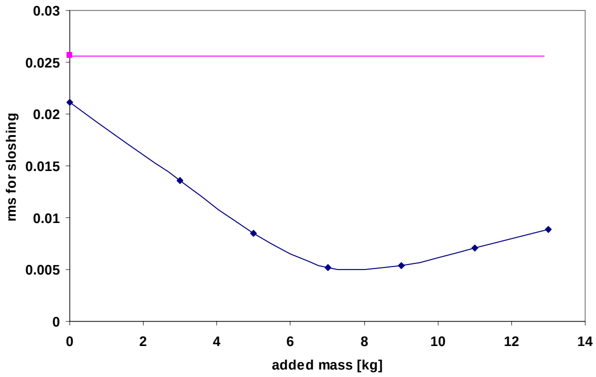



**Figure 4.** Variation of the rms sloshing magnitude in m with mass for rigid (▬) and flexible (▪) containers from numerical predictions.

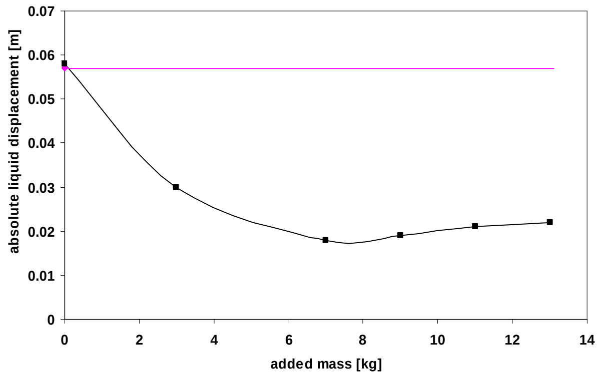



**Figure 6.** Same as in Figure 4, but for the absolute free surface displacement, experimental results.

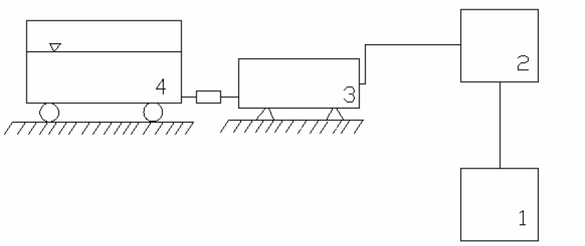



**Figure 5**. Schematic view of the experimental setup with base excitation. 1: personal computer, 2: power amplifier, 3: electromagnetic shaker, 4: container.

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