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LIQUID SLOSHING IN FLEXIBLE CONTAINERS, PART 2: USING A SLOSHING ABSORBER WITH A FLEXIBLE CONTAINER FOR STRUCTURAL CONTROL

M. GRADINSCAK, S.E. SEMERCIGIL and Ö.F. TURAN

Victoria University
School of Architectural Civil and Mechanical Engineering
Footscray Park Campus, PO Box 14428 MC
Melbourne, Victoria 8001 AUSTRALIA

ABSTRACT

Liquid sloshing may be employed for vibration control of resonant structures, similar to that of a classical tuned vibration absorber. For such a case, the sloshing frequency is tuned at a critical frequency of the structure in order to gain the benefits of the pressure forces as control forces. Such an absorber has the benefits of being effective and practically free of maintenance. The work presented in this paper utilizes a flexible container as a sloshing absorber. Numerical predictions are presented where a "tuned" flexible container can be advantageous over a rigid container for effective control.

INTRODUCTION

The concept of using sloshing forces for control of light and flexible strutures, has been the subject of intensive research. Abe et al. (1996) reported effective control of structural vibration using a U-tube with a variable orifice passage. Seto and Modi (1997) used fluid-structure interaction to control wind-induced instabilities. Reed et al. (1998) investigated tuned liquid dampers under large amplitude excitation. Nomura (1994) and Yamamoto and Kawahara (1999) used finite elements with moving grids based on the arbitrary Lagrangian-Eulerian formulation. Anderson et al. (2000a, 2000b) proposed a sloshing absorber of standing-wave type. Sakamoto et al. (2001) proposed a tuned sloshing damper using an electro-rheological fluid, utilizing both analytical and experimental methods.

All preceding works cited here deal with rigid containers as the sloshing absorber. There are no reported attempts in the literature to explore the possibility of employing a flexible container. This paper outlines the current research at Victoria University on the use of a flexible container as a sloshing absorber attached to a resonant structure.

As briefly discussed next, container flexibility introduces an additional tuning effect to that of an already existing tuning issue between the sloshing liquid and the structure to be controlled. Hence, a two-level tuning is required with a flexible container. The objective of this paper is to present the effect of this additional tuning effect. Extensive numerical predictions have been completed for this purpose. Selective cases from these trials are discussed below.

The subject matter in this paper is the second part of a two-part presentation. The first part deals with the possibility of suppressing liquid sloshing employing the container's flexibility, Gradinscak et al. (2006).

NUMERICAL PROCEDURE

A commercial finite element analysis package, ANSYS (2002), was used to model the dynamics of the container, sloshing liquid and the structure to be controlled. A schematic view of the model with a grid size of 50mm x 50mm, is given in Figure 1a. The sloshing absorber consisted of a rectangular aluminium container of 1.6 m x 0.4 m x 0.4 m in length, width and height, respectively. The wall thickness was 1 mm. Two-dimensional rectangular shell elements were used for the container walls with 1.5% critical damping in the fundamental mode. The container was filled with water to a depth of 0.3 m, corresponding to a mass of approximately 192 kg. The liquid was modelled using three-dimensional brick elements. Liquid had no damping. The modelling approach is the same as that mentioned in Part 1, Gradinscak et al. (2006).

Fluid-container interaction was achieved by coupling the displacement of the liquid and container walls in the direction normal to the container walls. A solid steel element was used to model the mass of the structure. The structure was attached with four springs to a rigid wall. The base of the container was connected rigidly to the top of the structure. The mass of the structure was 2000 kg which resulted in a mass ratio of 0.10 between the sloshing absorber and the structure to be controlled.

The sloshing absorber was orientated such that liquid sloshing was induced in the Z-direction in response to a 5-mm initial displacement given to the structure in the Y-direction. A transient solution was then obtained (with a time step of 0.01s and for a total duration of 20 s) by numerically integrating the resulting differential equations.

The concept of using liquid sloshing in flexible container to control structural vibration is similar to that of using a tuned absorber to control the excessive vibrations of a mechanical oscillator. The fundamental sloshing frequency of a liquid in a rigid container of the above dimensions is approximately 1.34 Hz (Anderson et al. 2000a). The natural frequency of the structure was also set (tuned) to this value to achieve strong interaction, similar to that of a classical tuned absorber.

In the case of a flexible container, there is a second level of tuning between the structure to be controlled and the container filled with liquid. As mentioned earlier, the primary objective of the presented work is to demonstrate the effect of this particular secondary tuning on structural response. Hence, case runs include different values of tuning frequencies of the flexible container. Different frequencies of the flexible container were obtained by symmetrically adding two lumped masses in the middle of the 1.6 m length, at the free top edge.

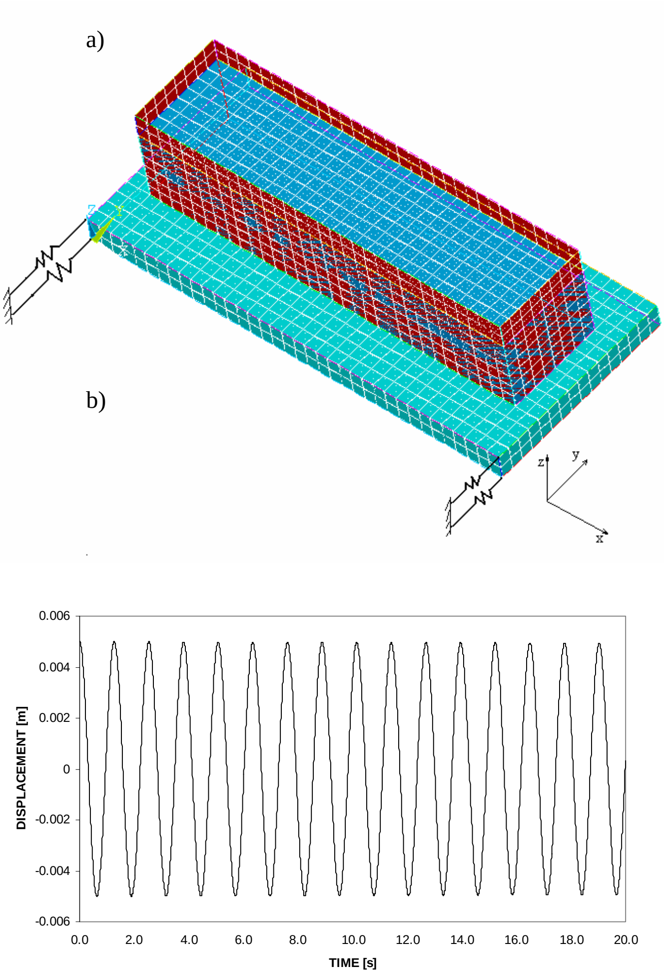

Figure 1. Showing (a) the computational model and (b) the displacement history of the structure after an initial displacement.

NUMERICAL PREDICTIONS

In Figure 1b, the displacement history of the structure in the Y-direction, is given without the sloshing absorber. Since no damping is included in the structure's model, the induced initial displacement of 5 mm remains unchanged indefinitely. Figure 1b is included here as the comparison base for all cases with the sloshing absorber.

The numerical predictions presented in Figure 2 are organised in two columns. With the exception of the rigid container case in Figure 2a, the left column contains the displacement histories of four nodes, two of the flexible container and two of the liquid. The histories of the two container nodes are the top and bottom ones (dark blue and red), whereas those of the liquid nodes (light blue and magenta) are in the middle. All nodes are selected to be at the level of the free surface, in the middle of the long side of the container. The container displacement is in the same direction as the initial disturbance, in the Y-direction, whereas the induced liquid motion is in the Z-direction. The second column contains the history of liquid sloshing which is the difference between the displacements of the two free surface liquid nodes. As sloshing refers to the out-of-phase motion of the liquid surface, the second column value is zero when there is no surface deflection and when the two liquid nodes move in-phase.

The first row, Figure 2a, contains the predictions obtained for the rigid container case. The following rows are for a flexible container at different tuning frequencies. As mentioned earlier, tuning of the flexible container is attempted by adding point masses to it, at the free top edge in the middle of the long sides of the container. The second row, Figure 2b, is for the no-added-mass case, whereas the following rows (in descending order) have pairs of results for the 3-kg, 5-kg, 9-kg, 11-kg and 13-kg point masses, respectively, in Figures 2c to 2g.

In Figure 3, the displacement histories of the structure are presented, by following the same order of cases as in Figure 2. It is important to remember that the displacement history of the uncontrolled case Figure 1b, is the comparison base for all cases in Figure 3. Again, following the same order, the corresponding frequency spectra are given in Figure 4. In this figure, liquid sloshing spectra are marked with red, flexible container displacement spectra are marked with blue, and the structural displacement spectra are marked with green.

In Figure 2, the first row corresponds to the case with a rigid container. In the left column in Figure 2a, displacement of only the two liquid nodes are given which undergo an almost perfectly out-of-phase motion, in response to the initial displacement given to the structure. The sloshing magnitude in the second column is 60 mm. The clear beat in the envelope is the result of the imposed "tuning" at 1.34 Hz between the sloshing frequency and the natural frequency of the structure. The beat indicates strong interaction, and the back-and-forth flow of energy between the liquid and the structure. The beat envelope is at a peak when most of the kinetic energy is with the sloshing liquid. The beat envelope diminishes to approximately zero, and the free surface becomes flat temporarily, when the energy is transferred to the structure. The same clear beat envelope is also apparent in the displacement history of the structure in Figure 3a, but out-of-phase with that of Figure 2a. The peak displacement of the structure is 5 mm, the same as in Figure 1b, since neither the structure nor the liquid has any means of dissipating energy. In Figure 4a, the tuning is clearly marked with the sharp trough at 1.34 Hz, along with the two spectral peaks at approximately 1.2 Hz and

1.45 Hz (which are responsible for the beat envelope with a 4-second period). The small spectral peak at approximately 2.3 Hz marks the second sloshing mode.

In the second row of Figure 2, the flexible container case is shown with no added mass in Figure 2b. With the dimensions listed earlier, and with a 1-mm wall thickness, the container is clearly off-tuned. In the left column, the top and bottom histories, corresponding to the displacement of the container walls, show large deflections at frequencies clearly different than that of the liquid nodes, in the middle. In the right column, the beat of the envelope is much less apparent than the case discussed for the rigid container. The peak sloshing magnitude is approximately 80 mm, as compared to 60 mm for the rigid container case. In Figure 3b, the displacement history of the structure still suggests a beat, although it is somewhat less organised than that in Figure 3a. As a result of container oscillations, the peak displacement of the structure is attenuated to 4 mm, from the initial displacement of 5 mm, by the end of the 20-second simulation. Hence, the amplification of the sloshing amplitude from 60 mm to 80 mm is not necessarily detrimental to the control action on the structure, which is the primary objective of the investigation. In addition, despite the off-tuned container, it is interesting to note that the oscillation frequency of the structure within the envelope is quite comparable to that of sloshing, shown in the second column in Figure 2b.

The spectral distributions in Figure 4b are rather complicated, partly due to the presence of multiple modes of the container in this off-tuned case. Multiple spectral peaks make it difficult to comment on their relative importance, with the exception of the original sloshing frequency of approximately 1.34 Hz. As a result of lack of any coherent interaction with its flexible container, sloshing largely reverts to its original frequency, also forcing a response from both the structure and the container at the same frequency.

In the third row, in Figure 2c, the predicted displacement histories are shown when a pair of 3 kg masses is added to the container. One immediate observation in the left column is the lowered frequency in the oscillations of the container. The oscillations of the two liquid nodes are mostly in-phase, especially during the last 5 seconds of the simulation, indicating suppressed sloshing. There is a clear beat in the second column, and the sloshing magnitude is reduced to approximately 20 mm towards the end of the simulation. Beat is also clear in the structural oscillations in Figure 3c, with a period of 8 seconds. In addition, by the third peak of the beat envelope, at around 17 seconds, the 5-mm initial deflection is reduced to approximately 2 mm.

In Figure 4c, the dominant structural (green) and sloshing (red) response is at 1.4 Hz, and it is split by the spectral peak of the flexible container (blue). This split and the resulting double spectral peaks are responsible for the beat envelope with a long period. The flexible container also has a spectral peak of significant magnitude around 0.7 Hz.

Observations with 5-kg added mass are quite close to those with 3 kg, as shown in Figures 2d, 3d and 4d. One exception is the further suppression of the sloshing magnitudes to about 15 mm, as shown in the second column in Figure 2d. This case is included to show the transition of the split double peaks in the response of the structure and sloshing in Figure 4d.

Observations with 9-kg added mass, correspond to the most effective tuning reported earlier in Part 1 of this two-part paper for the suppression of the liquid motion in a flexible container of the same dimensions as the one used here. In Figure 2e, the liquid surface moves in almost perfect phase, resulting in a virtual elimination of sloshing as shown in the second column.

In Figure 3e, the beat period is about 5.5 s, and the peak of the last beat around 18 s, is reduced to under 1.5 mm. The two dominant peaks are now clearly separated for both the structure and the liquid in Figure 4e. In a way, these two peaks around 1.3 Hz and 1.45 Hz behave quite similarly to the two peaks of the case with the rigid container in Figure 4a. The difference, of course, is the drastically reduced magnitudes as a result of the container flexibility. It is also interesting to note that the spectral distribution of the flexible container starts to favour lower frequencies.

With further increases of the added mass to 11 kg and 13 kg, in frames f and g of the respective figures, sloshing magnitude starts to grow, as the container flexibility now starts to de-tune from the dynamics of sloshing. However, the beat in the structure's response is still very clear in Figures 3f and 3g, with a further reduction of the peak response to about 1 mm, around 17 seconds. Hence, the liquid in the container and the structure seem to interact quite strongly, almost ignoring the loss of tuning of the container. This observation is supported by the spectral distribution given in Figures 4f and 4g. Although simulated, any further increase in the added mass is not reported here, as the practicality of the suggested tuning process is lost for excessive values of added mass.

CONCLUSIONS

Numerical predictions with standard finite element analysis are presented to show the effect of the container flexibility of a sloshing absorber in suppressing the transient oscillations of a resonant structure. The mass of the sloshing absorber is limited to 10% of that of the structure. Flexible container has 1.5% structural damping in the equivalent sense, as the only damping in the system. Although, there are trends in the simulated response which could not yet be reasoned with confidence, attenuations in the order of 80% are suggested in the transient response of the structure with the use of container flexibility as a design parameter. Reported observations are certainly encouraging for further investigation. Part of this further investigation is to attempt to validate the numerical predictions.

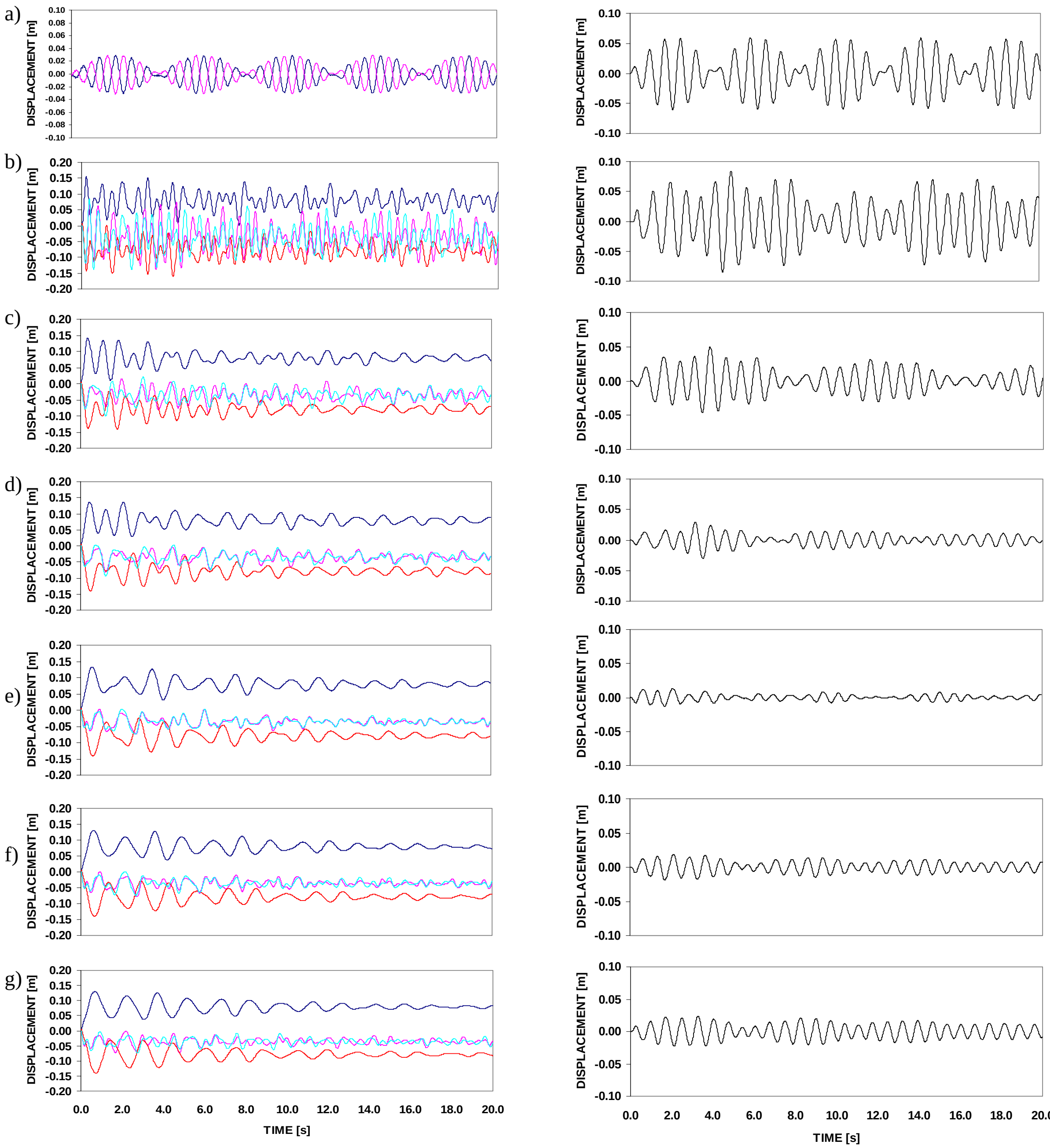

Figure 2. Displacement histories of two container nodes (dark blue and red) and two free surface nodes (light blue and magenta) (left column), and of liquid sloshing (right column). Cases of (a) the rigid container, and flexible container with (b) no added mass, and (c) 3-kg, (d) 5-kg, (e) 9-kg, (f) 11-kg and (g) 13-kg added mass.

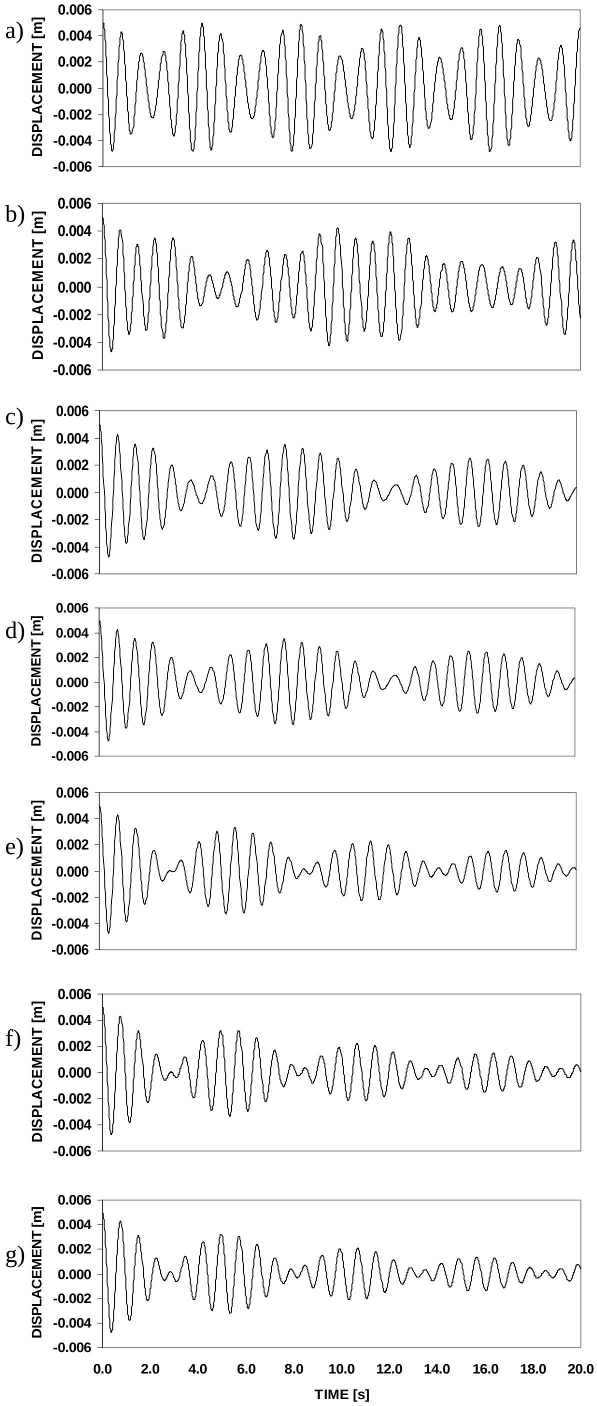

Figure 3. Structural displacement history for the same cases as in Figure 2 presented in the same order.

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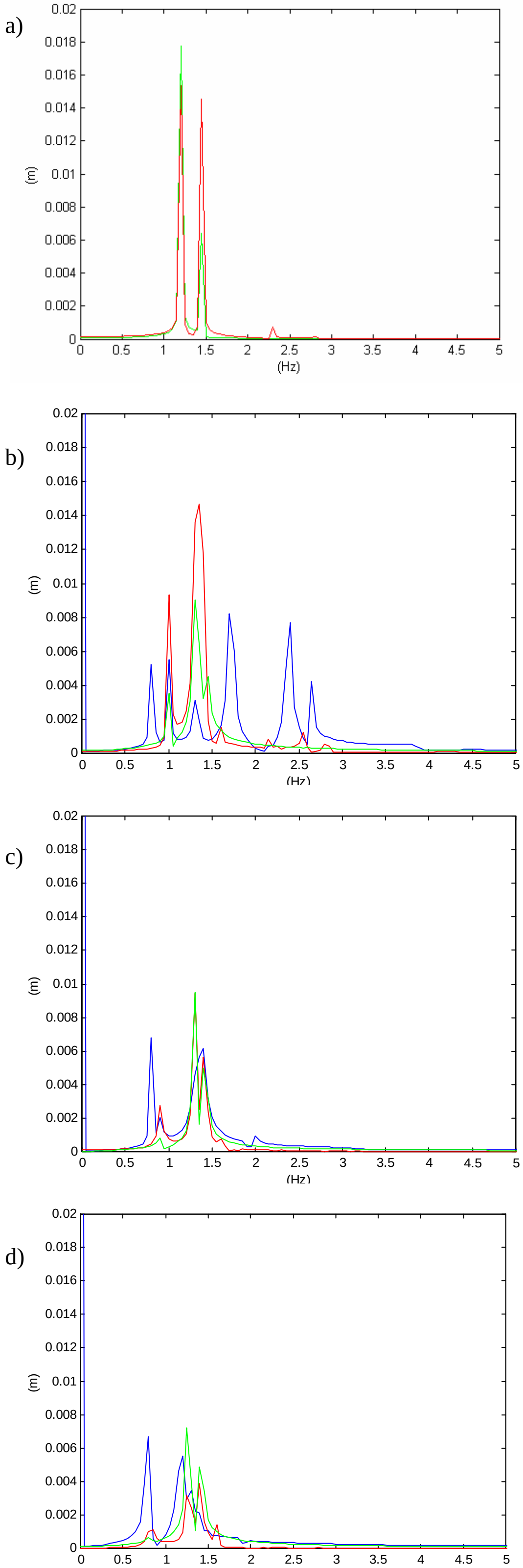

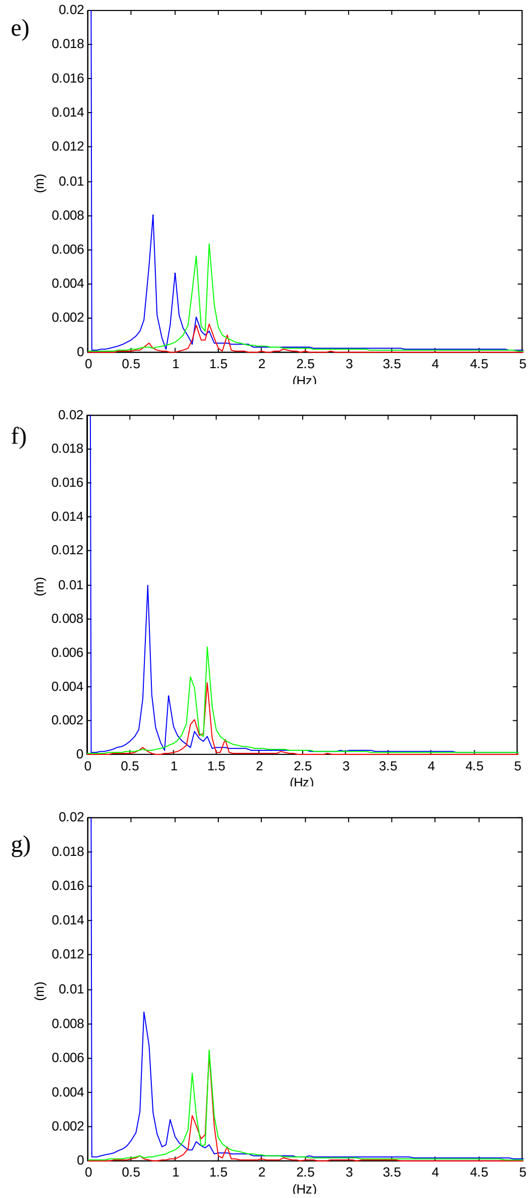

Figure 4. Frequency spectra of container displacement (blue), liquid sloshing (red) and structural displacement (green) for (a) the rigid container, and flexible container with (b) no added mass, and (c) 3-kg, (d) 5-kg, (e) 9-kg, (f) 11-kg and (g) 13-kg added mass. (The magnitudes of the structural response spectra are multiplied by 10 to be able to display them with the same scale as the container displacement and sloshing amplitude spectra.)