

A Sloshing Absorber with a Flexible Container

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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 is practically free of maintenance. The work presented in this paper utilizes a flexible container partially filled with water, as the sloshing absorber. Numerical predictions are presented where a “tuned” flexible container can be advantageous over a rigid container for effective control.

1. INTRODUCTION

The concept of using sloshing forces for control of light and flexible structures, has been a subject of interest in the literature. Abe et al. [1] reported effective control of structural vibration using a U-tube with a variable orifice passage. Seto and Modi [2] used fluid-structure interaction to control wind-induced instabilities. Reed et al. [3] investigated tuned liquid dampers under large amplitude excitation. Nomura [4] and Yamamoto and Kawahara [5] suggested finite elements with moving grids, based on the arbitrary Lagrangian-Eulerian formulation. Anderson et al. [6] proposed a sloshing absorber of standing-wave type. Sakamoto et al. [7] 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 summarises the current research at Victoria University on tuning flexible containers for structural control.

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. The additional tuning is required to account for the energetic behaviour of the flexible container, in response to the dynamic forces from the sloshing liquid and the oscillations of the structure to be controlled.

Extensive numerical predictions have been completed to investigate the problem of tuning. Selective cases are discussed below. Full details may be found in References 8 and 9. No experiments are presented here. However, the design of a flexible container to achieve sloshing suppression through tuning, has been verified with experimental observations earlier [9].

2. NUMERICAL PROCEDURE

A standard finite element analysis package, ANSYS [10], 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 1(a). The sloshing absorber consisted of a rectangular aluminium container of 1 mm wall thickness and 1.6m x 0.4m x 0.4m in length, width and height, respectively. Two-dimensional rectangular shell elements were used for the container walls with 1.5% critical damping in the fundamental mode (effects of different damping values will be presented at the end of the discussion in Section 3). 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 viscous dissipation.

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 element was used to model the mass of the structure. The structure was attached with four springs to a rigid wall. The container was attached rigidly on the structure. The mass of the structure was 2000 kg which resulted in a mass ratio of slightly under 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. The fundamental sloshing frequency of a liquid in a rigid container of the same dimensions is approximately 1.34 Hz [6]. 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 a range of structural critical 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.

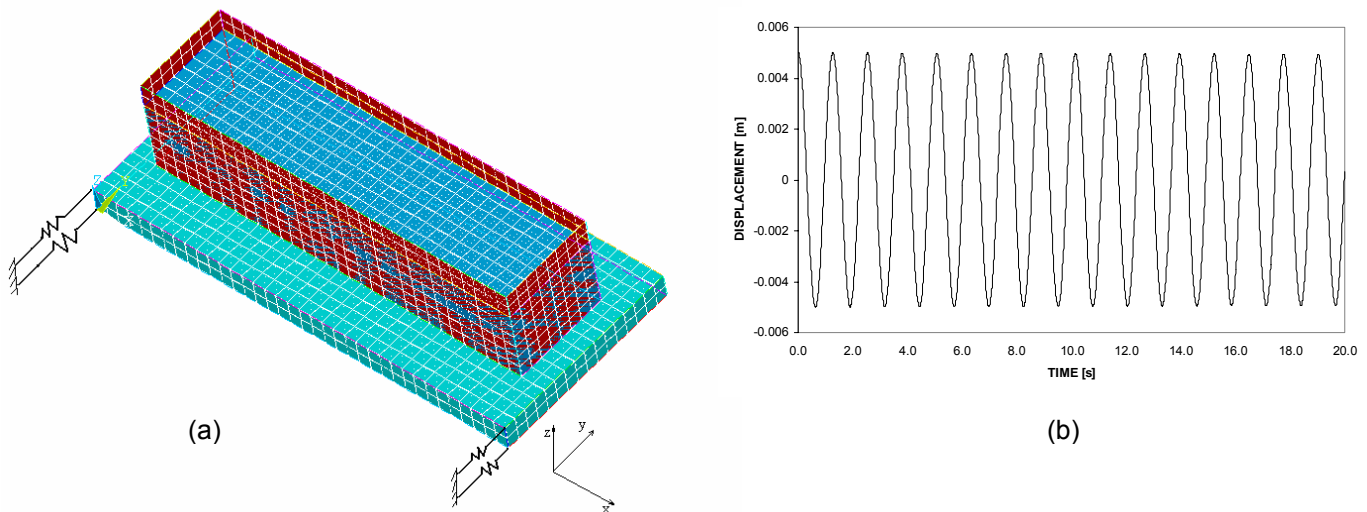


Figure 1. Showing (a) the computational model and (b) the displacement history $y(t)$ of the structure after an initial displacement.

3. NUMERICAL PREDICTIONS

In Figure 1(b), the displacement history of the structure in 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 1(b) is included here as the comparison base for all cases with the sloshing absorber.

The numerical predictions presented in Figure 2 represent the displacement histories of four cases. Frames (a) to (d) correspond to the cases of rigid container, flexible container with no added mass, with 9 kg and with 13 kg added mass, in descending order. As mentioned in the preceding section, additional masses are used to vary the structural critical frequencies of the flexible container. The 9 kg mass case represents the tuned flexible container for most effective suppression of sloshing [8,9]. No mass and 13 kg mass cases are outside this tuning, at varying severities.

With the exception of the rigid container case in Figure 2(a), each frame has 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 Y-direction, whereas the liquid motion takes place in Z-direction.

In Figure 3, the displacement histories of the structure are presented, by following the same order of Figure 2. It is important to remember that the uncontrolled displacement history in Figure 1(b), is the comparison base for all cases in Figure 3. Again, following the same order, the frequency spectra are given in Figure 4. In this figure, liquid sloshing is marked with red, flexible container displacement is marked with blue, and the structural displacement is marked with green. Sloshing (red) corresponds to the difference of the displacements of the two free surface liquid nodes, to present the most detrimental out-of-phase surface motion.

In Figure 2(a), displacement of the two liquid nodes are given which experience a perfectly out-of-phase motion, in response to the initial displacement of the structure. The peak-to-peak magnitude at the wall is 60 mm. The clear beat in the envelope is the result of “tuning” the sloshing frequency and the natural frequency of the structure at 1.34 Hz. 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 when the kinetic energy is transferred to the structure. The same clear beat is also apparent in the displacement history of the structure in Figure 3(a), but out-of-phase with that of Figure 2(a). The peak displacement of the structure is 5 mm, the same as in Figure 1(b), since neither the structure nor the liquid has any means of dissipating energy. In Figure 4(a), 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 an approximately 4-second period).

In Figure 2(b), the flexible container case is shown with no added mass. The container is clearly off-tuned. The top and bottom histories (dark blue and red), corresponding to the displacement of the container walls, show large deflections at frequencies clearly different than those of the liquid nodes (light blue and magenta). Peak-to-peak liquid displacements reach values up to 120 mm, decreasing to about 80 mm, towards the end of the 20 s simulation period. These values are clearly larger than the 60 mm displacement of the rigid container case. In Figure 3(b), the displacement history of the structure, the beat is much less apparent than the case discussed for the rigid container. The longer beat period of about 10 s, is the result of the double peaks at approximately 1.4 Hz and 1.5 Hz in Figure 4(b). A weaker beat is also discernable due to the interaction of spectral peaks at about 1 Hz and 1.5 Hz, with a period of about 2 s.

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 is not necessarily detrimental to the control action on the structure.

Despite the fact that the container is clearly off-tuned, it is interesting to note that the oscillation frequency of the structure (green) within the envelope is quite comparable to that of sloshing liquid (red), in Figure 4(b). The off-tuned container has spectral peaks at the same frequencies forced by the sloshing liquid and the structure, and additional spectral peaks quite outside of those of the liquid and the structure at 0.8 Hz, 1.7 Hz, 2.4 Hz and 2.7 Hz.

The spectral distributions in Figure 4(b) are rather complicated, as compared to those in Figure 4(a), due to the presence of multiple modes of the flexible 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 this frequency.

Any addition of mass to the container has an immediate effect of lowering its critical frequencies quite dramatically. The double peak, pointed out earlier in the response of the structure, is further split apart and continue to be responsible for the beat in the histories of the structural displacement.

Observations with the 9-kg added mass, correspond to the most effective tuning reported earlier [8, 9] for the suppression of the liquid motion. In Figure 3(c), the liquid surface moves in almost perfect phase, resulting in a virtual elimination of the most damaging liquid sloshing in the fundamental mode. In Figure 3(c), the beat period is about 5.5 s, and the peak of the last beat around 18 s, is reduced to smaller than 1.5 mm. The two dominant peaks are now clearly separated for both the structure and the liquid in Figure 4(c). In a way, these two peaks around 1.3 Hz and 1.45 Hz are quite similar to those of the rigid container in Figure 4(a). 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 now favours lower frequencies.

With further increases of the added mass from 9 kg, the flexible container starts to de-tune clearly from the dynamics of sloshing - 13 kg is given in Figures 2(d), 3(d) and 4(d). However, the beat in the structure's response is still present in Figure 3(d), 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 also supported by the spectral distribution given in Figure 4(d).

A collective summary of relevant simulations is given in Figure 5. In Figure 5(a), the root mean square (rms) averages of sloshing amplitudes are given for different values of added mass, whereas the rms averages are shown in Figure 5(b) for the structural displacement. The various values used equivalent viscous damping ratio of flexible container, are 0 (◆), 1.5% (■), 5% (▲), and 10% (●). It should be mentioned here that rms averages are presented here as a means of rank ordering effectiveness.

In Figure 5(a), except for the no added mass case, a flexible container gives a smaller sloshing magnitude than the rigid container (—). The smallest sloshing is around 7kg to 9 kg which is in close agreement with the tuning suggested earlier to suppress sloshing [9]. The tuning effect is most apparent for the undamped container (◆), and it diminishes with increasing damping. For the 10% critical damping case (●), little difference could be observed within the range from 5 kg to 13 kg.

In Figure 5(b), all sloshing absorbers, including the rigid container, suggest a smaller structural displacement as compared to the uncontrolled case (—) which retains the 5-mm initial displacement indefinitely. A negative slope can be observed in all flexible container cases, with the exception of the undamped container (◆), for increasing added mass. Again, except for the change from no mass to 3 kg, the change is gradual with diminishing sensitivity as the container's damping increases.

4. 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 about 10% of that of the structure. Flexible container has 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 1.5% structural damping of the container) 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 with prototype testing.

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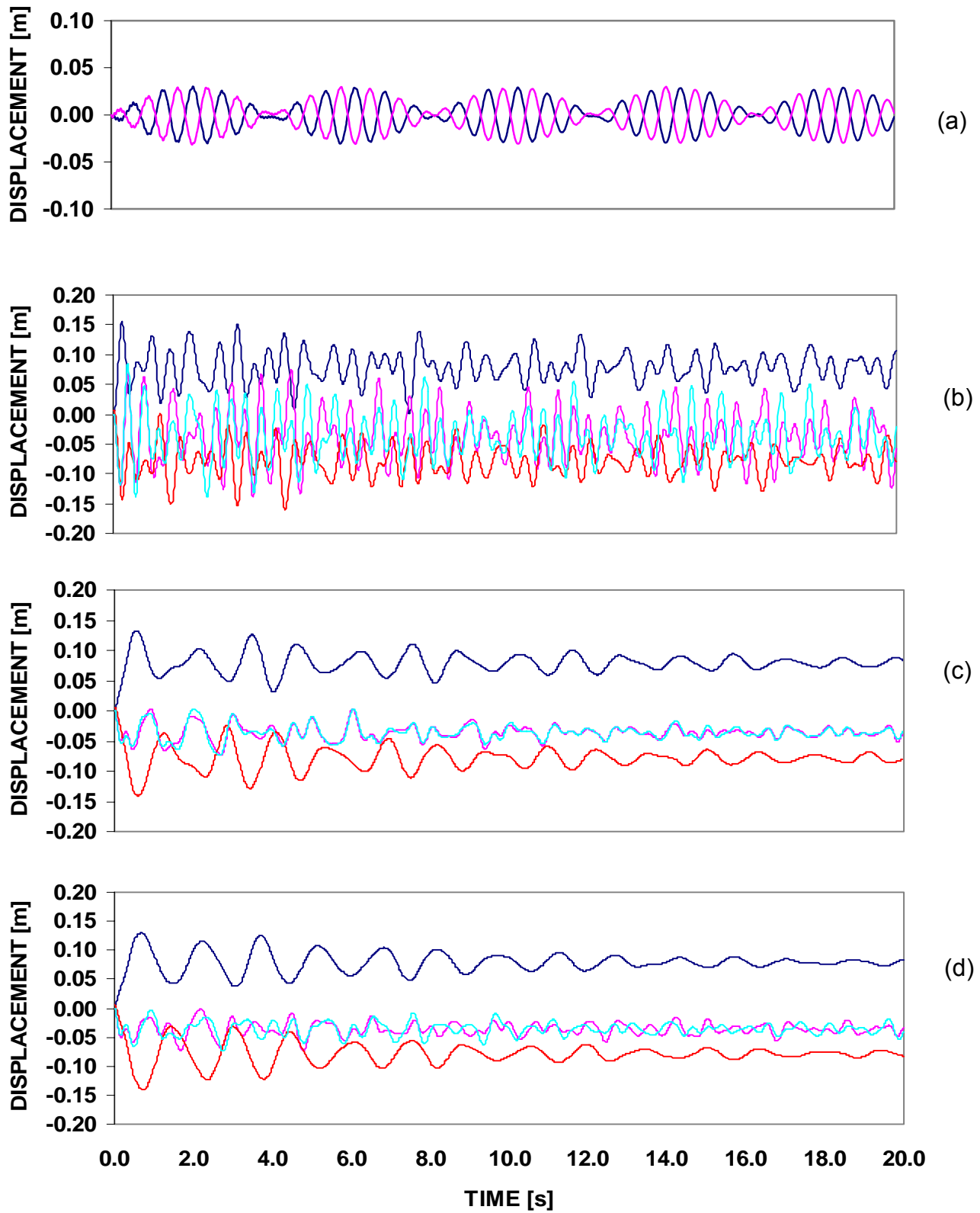


Figure 2. Displacement histories of (a) the liquid nodes (magenta and light blue), and container (black and red) of (a) the rigid container, (b) flexible container with no mass (c) 9 kg mass and (d) 13 kg mass.

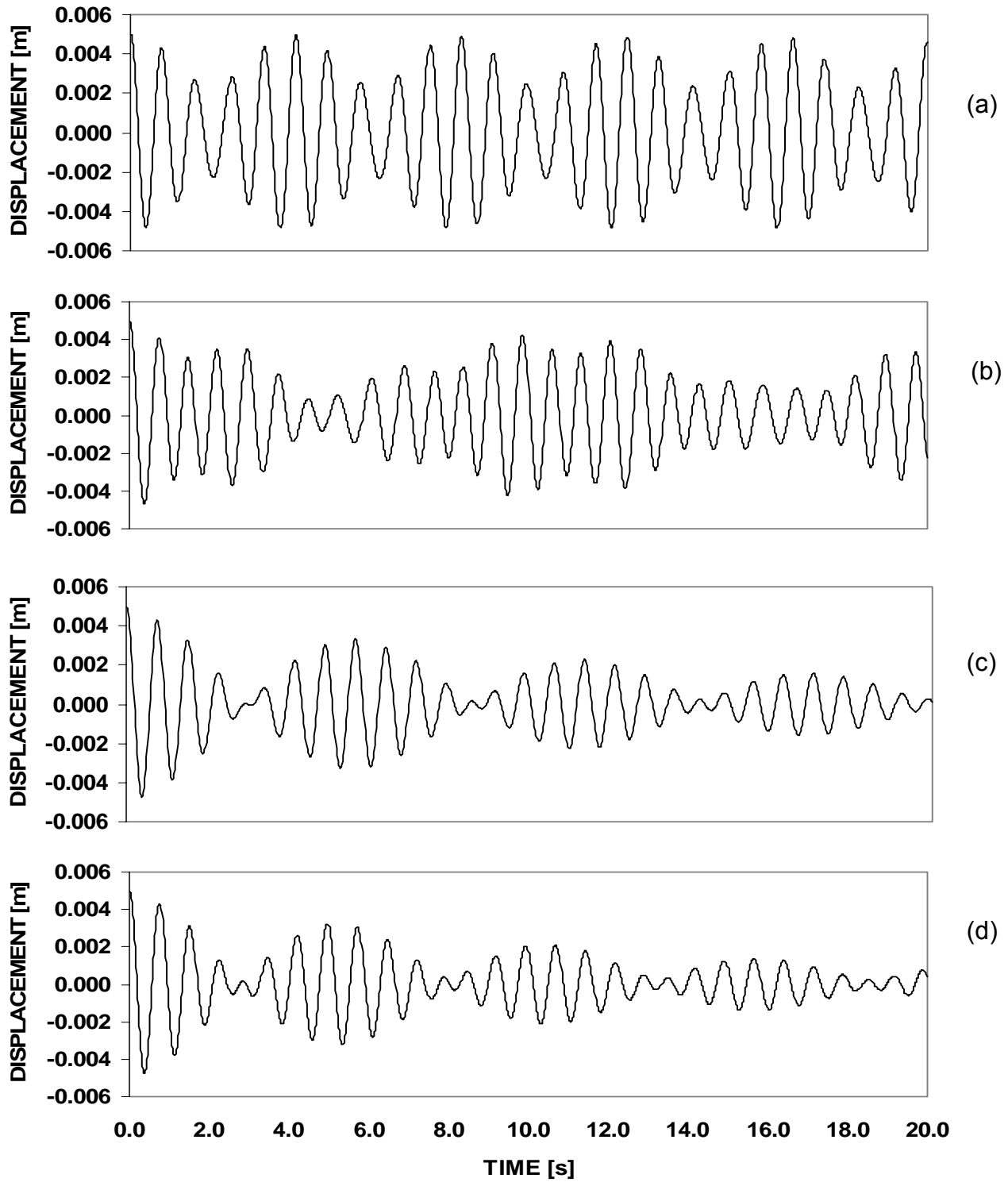
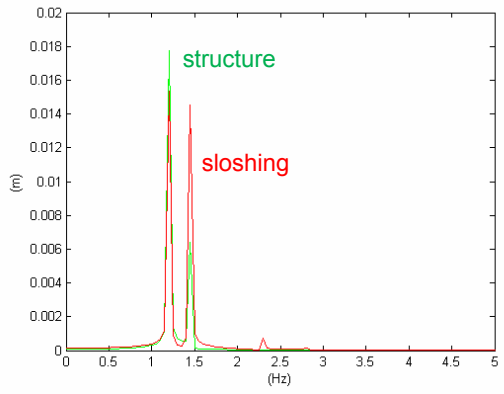
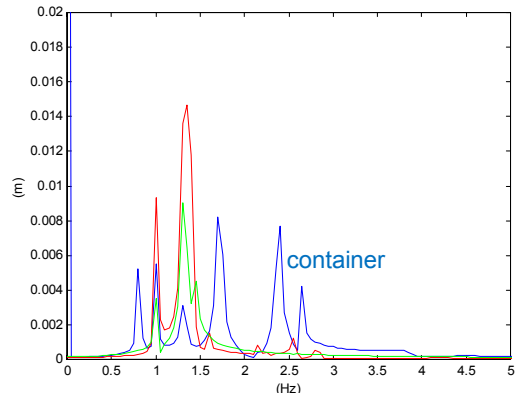


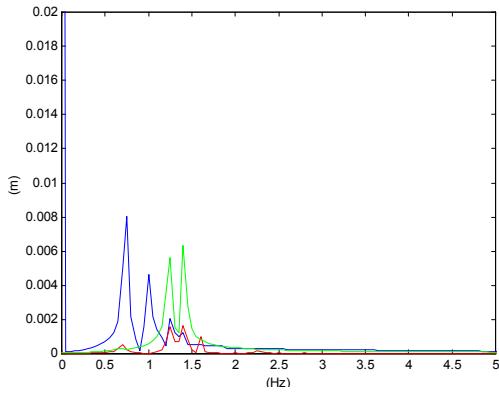
Figure 3. Displacement histories of the structure in the same order as in Figure 2.



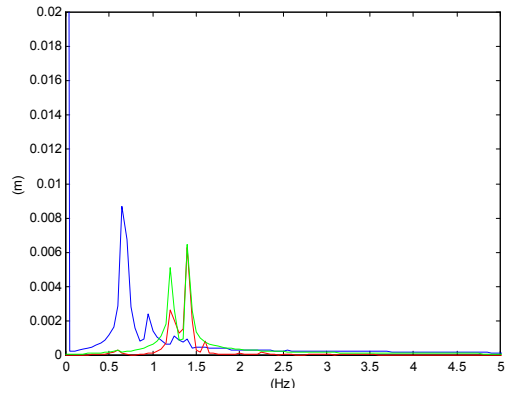
(a)



(b)



(c)



(d)

Figure 4. Spectral distribution of sloshing (red) container (blue) and the structure (green) in the same order as in Figure 2.

*Structural spectrum is multiplied by 10 to enable display with the same scale as that of the sloshing spectrum.

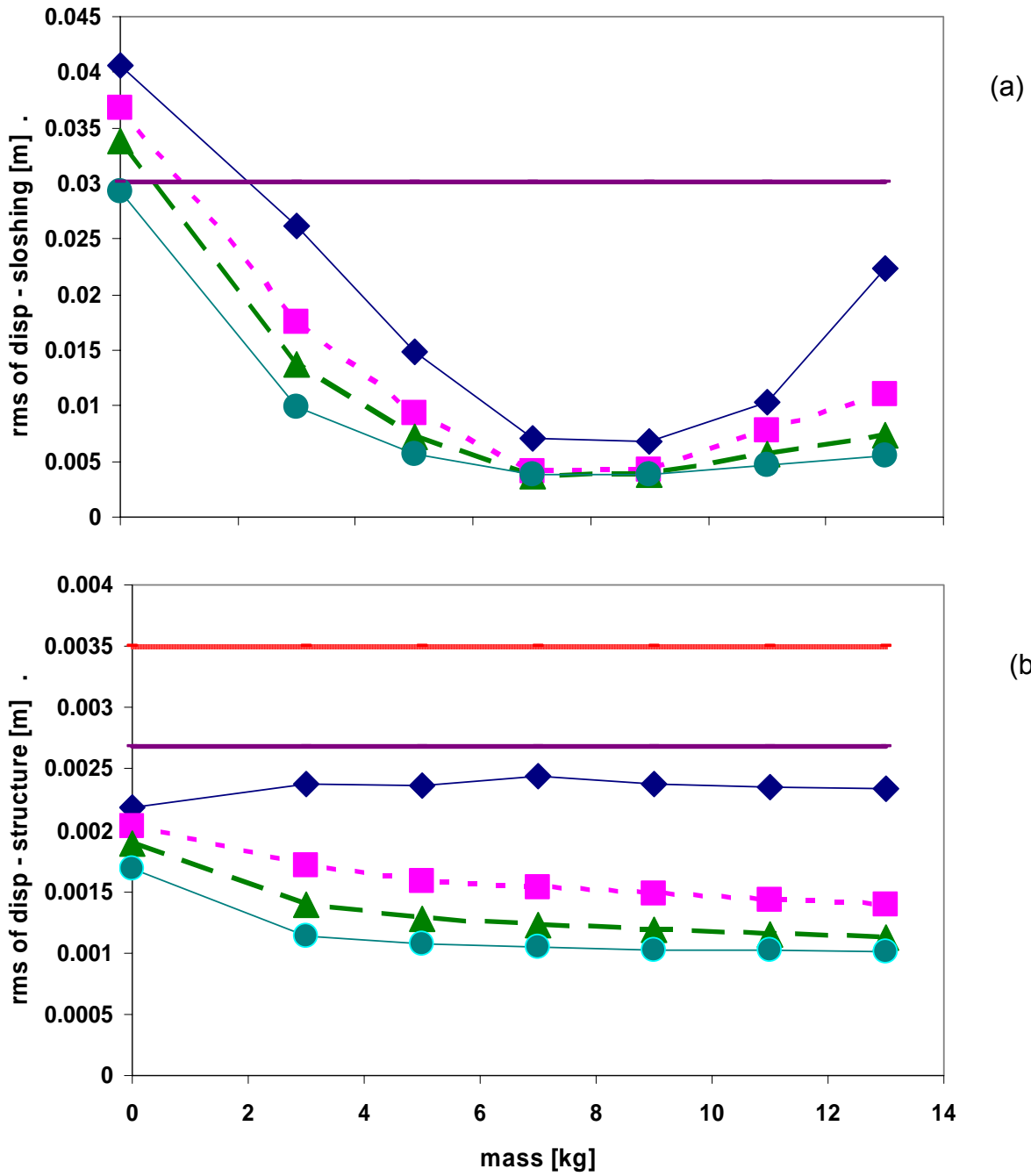


Figure 5. Variations of the rms of (a) sloshing amplitude and (b) structural displacement with added mass.

(—) structure alone, (—) rigid container; and flexible container with equivalent structural damping ratios of 0 (◆), 1.5% (■), 5% (▲), and 10% (●).