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Control of Liquid Sloshing in Flexible Containers: Part 1. Added Mass

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Abstract

Liquid sloshing is the low frequency oscillation of a liquid in a partially full container. Intentional container flexibility has been employed in this study to suppress excessive levels of liquid sloshing. Part 1 of this two-part paper is regarding the effectiveness and optimization of added mass for this purpose.

Introduction

The liquid in an open container can oscillate at discrete natural frequencies. The liquid motion, sloshing, at the lowest of these frequencies is of concern in this study as shown in Figure 1. In this figure, L indicates the width of the container (wavelength), and H the height of the static liquid. The shaded area of the diagram illustrates the shape of the free surface at the fundamental mode. It is critical to predict and to control liquid sloshing in order to maintain safe operation in ground and marine transport of liquid cargo, aerospace vehicles and earthquake-safe structures. A numerical model is presented in this study, which enables prediction of liquid sloshing. With this model, the use of container flexibility is investigated in order to control sloshing. Tuning is achieved with added masses.

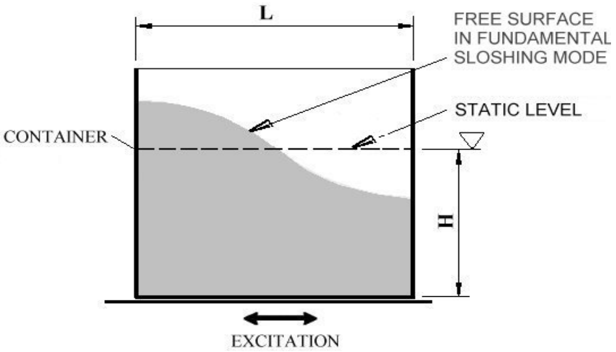

Figure 1. Sloshing in a rigid container.

Anderson [1], first investigated the possibility of using container flexibility for the control of liquid sloshing. Gradinscak et al. [3] 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 is previously studied [4] to provide insight for the tuning process. In this paper, further findings are presented towards an optimal flexible container design. The objective is to explore the possibility of enhancing the control action.

Numerical Model and Procedure

An aluminum rectangular prism of 1.6 m x 0.4 m x 0.4 m has been chosen as the container. The wall thickness of the container is 1 mm. With this 0.4 m by 0.4 m cross section, the liquid level is fixed at 0.3 m (in the Z direction). Working liquid is water. A finite element analysis (FEA) package, ANSYS, is used to model both the container and liquid dynamics [2]. A schematic view of the geometric model is given in Figure 2.

The container walls are modelled with standard shell elements of 0.05 m x 0.05 m size. A 1 % equivalent viscous critical damping is used to represent structural energy dissipation in the first two modes. Three dimensional cubic fluid elements are used for the liquid of the same size as the container. Grid independence has been verified. Similarly, a 10-ms integration step has been found to be sufficiently small for the accuracy of numerical predictions.

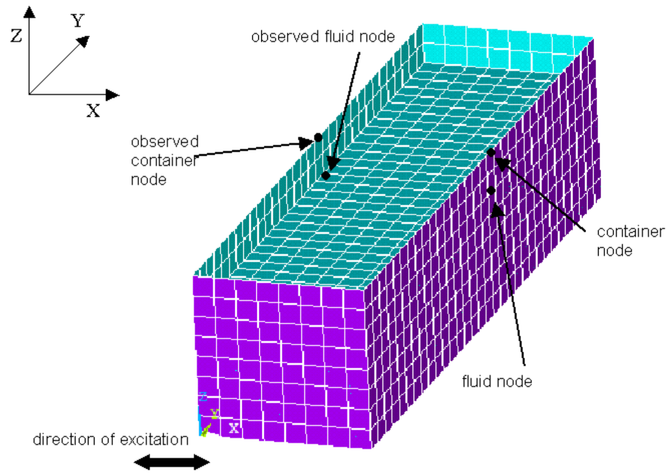

Figure 2. The numerical model and the location of the observed nodes.

A conventional tuned absorber is an auxiliary oscillator attached to a structure to be controlled. Normally, the natural frequency of the absorber is tuned to that of the structure 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 acts like the tuned absorber. The objective is to tune the container's dynamics in such a way as to minimize liquid sloshing.

The tuning process may be implemented with the addition of masses to the container [4]. Varying point masses, of 1 kg to 45 kg each, are added on the container walls, at the two locations marked as the observed container nodes in Figure 2. These nodes have also been chosen to represent the container's response in the X direction. Liquid response is represented by the displacement of the two nodes at the free surface, directly aligned with those of the container nodes, in the Z direction.

Sloshing is induced by imposing a sinusoidal base displacement of one cycle in the X direction. The peak-to-peak base displacement is 10 mm with a frequency of 1.34 Hz. This frequency corresponds to the theoretical sloshing frequency of a rigid container of the same dimensions [5].

In the numerical model, the starting instant corresponds to the sudden presence of a rather large amount of water in the undeformed container. In response, the container immediately attempts to assume a deformed shape to accommodate the water's presence. This attempt results in oscillations of the container and the fluid. However, these fluid oscillations are simply an up-and-down motion of the flat surface, and quite different than sloshing. Originally, simulations were performed for 40 seconds to allow the container to assume its static equilibrium for the first 20 seconds, and then, the transient base disturbance mentioned earlier was applied. However, due to relatively poor energy dissipation, a 20 second period was insufficient to reach the static equilibrium. As a result, the in-phase displacements of the free surface continued, along with the out-of-phase sloshing displacements. The difference between the vertical displacements of the two free surface nodes, allowed the extraction of the out-of-phase motion of the free surface, which is referred as the "sloshing history".

When the same cases were simulated starting with the application of the base disturbance without waiting to reach the static equilibrium first, it was observed that the out-of-phase "sloshing history" of the free surface was virtually identical to the earlier ones. For these cases, in-phase and out-of-phase liquid motion took place simultaneously. However, the subtraction process made it possible to observe the relevant "sloshing history" avoiding the initial 20-second idle period. In this paper, selected cases are presented for a total duration of 20 seconds where the base disturbance is given at the start of the simulation period. This point is further examined in Part 2.

Results and Discussion

Sloshing histories and the corresponding frequency spectra for selected cases of a rigid container and a flexible container with no added mass, 7-kg, and 21-kg added masses, are presented in Figures 3(a) to 3(d). Sloshing histories given in the first column of Figure 3, represent the out-of-phase displacement of the free surface.

The sloshing history for the rigid container in Figure 3(a), sustains a peak amplitude of around 40 mm. This amplitude is approximately the same for the flexible container case in Figure 3(b) with no added mass. The gradual decay is due to 1% critical damping of the structure. The optimal tuning range is around 7 kg of added mass [4]. For this case, the peak sloshing amplitude decreases to 10 mm - 15 mm in Figure 3(c). Sloshing amplitude further increases to about 30 mm with 21-kg added mass in Figure 3(d).

In the second column of Figure 3, the frequency spectra of the container displacement (——) and sloshing (……) are presented. For the rigid container in Figure 3(a), the fundamental liquid sloshing frequency is indicated to be around 1.4 Hz, quite close to 1.34 Hz [5]. Another small spectral peak is around 2.3 Hz, possibly corresponding to a harmonic of the fundamental mode.

The frequency of the highest sloshing peak in Figure 3(b), is around 1.2 Hz. The flexible structure seems to be driven strongly by the liquid at this frequency. In addition to the sloshing driven structural peak at 1.2 Hz, there are two major spectral peaks, one around 0.75 Hz and the other around 1.7 Hz. In Figure 3(b), spectral peaks around 1.4 Hz and 2.3 Hz can still be noticed for sloshing.

With 7-kg added mass in Figure 3(c), the structure appears to have two dominant spectral peaks. These peaks are around 0.7 Hz and 1.1 Hz. The magnitude of second spectral peak at 1.1 Hz, is comparable to that of the first peak. The control effect on sloshing of the second structural peak is clear, practically eliminating any response from the liquid motion between frequencies of 0.9 Hz and 1.4 Hz. In contrast to the second spectral peak, the first spectral peak of the structure at 0.7 Hz seems to have an adverse effect on sloshing control. The structure seems to drive the liquid at this frequency.

In Figure 3(d), for 21-kg added mass, sloshing around 1.4 Hz becomes significant again, indicating that the interaction of 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.

In Figures 4(a) to 4(c), the left column is the cross-correlation between sloshing amplitude and structural displacement for a flexible container with no added mass, 7-kg added mass and 21-kg added mass, respectively. The horizontal axis represents the number of integration steps of 10 ms each over the total time of 20 s. The right column is the corresponding cross-spectrum for the same cases. In the cross-correlation graphs, it is seen that the fluid-structure interaction is significantly lost after 7 kg added mass.

In the cross-spectrum plots, the dominant frequency of communication can be viewed at different added masses. As the structure and fluid strongly drive each other, a clear large spectral peak is observed. For the no added mass case and within the tuning region, there is a clear dominant frequency as seen in Figures 4(a) and 4(b). The dominant frequency for the no added mass case in Figure 4(a) is close to the fundamental fluid frequency. This result suggests that the system is mainly driven by the fluid. The dominant spectral peak in the tuning range, on the other hand, is around that of the structural fundamental frequency, which similarly is an indication that the fluid is being driven by the container at this time.

From Figures 3(c) and 4(b), it is seen that the structure is significantly affecting the liquid response in the tuning range. In addition to suppressing the liquid response at certain frequencies, the structure is driving the liquid at other frequencies, as previously mentioned. Therefore, if this second detrimental effect can be eliminated, it should certainly be possible to improve the design of a flexible container. Current work is in this direction to identify the structural mode shapes to encourage the control effect, and to discourage the driving effect on liquid sloshing.

A summary of the tuning process is presented in Figure 5 with the root mean square averages of sloshing amplitudes. The minimum sloshing amplitude is for about 7 to 8-kg added mass on the flexible container, corresponding to better than 80% attenuation as compared to the rigid container (solid red line). 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 on the right hand side of the best performance where the added mass may be allowed to be somewhat larger than the optimal without significant loss of effectiveness.

Conclusions

With proper tuning of a flexible container, a net reduction of about 80% is possible in the rms liquid sloshing amplitudes, as compared to that in the rigid container. An optimal value of added mass exists around 7 kg for the dimensions used here. This paper represents a progress report on attempts to improve the control effect on sloshing.

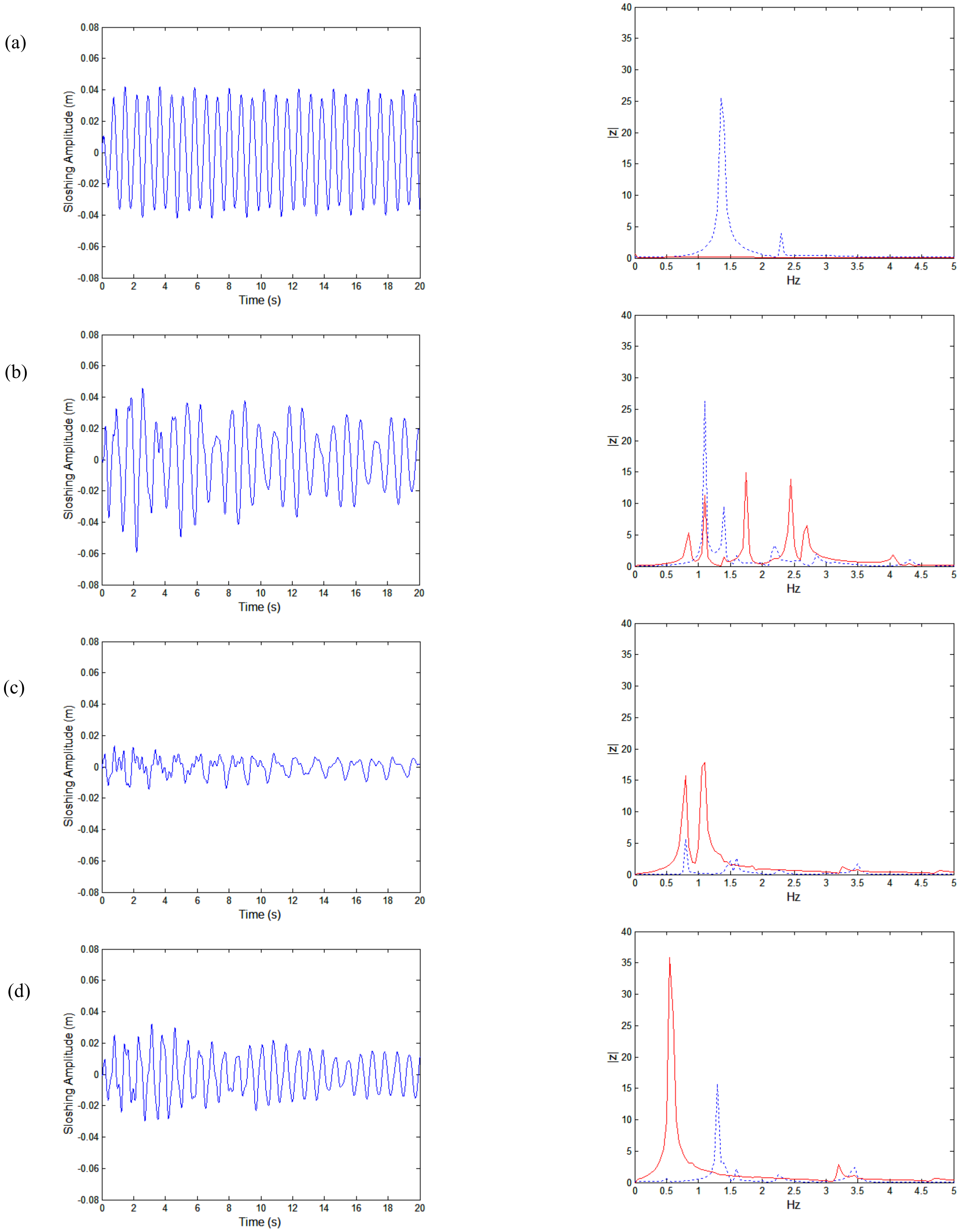

Figure 3. First column: Predicted sloshing histories (a) Rigid container. Flexible container with added point masses: (b) 0 kg, (c) 7 kg, (d) 21 kg. Second column: FFT of sloshing liquid (dashed) and structural vibration (solid) for the same cases.

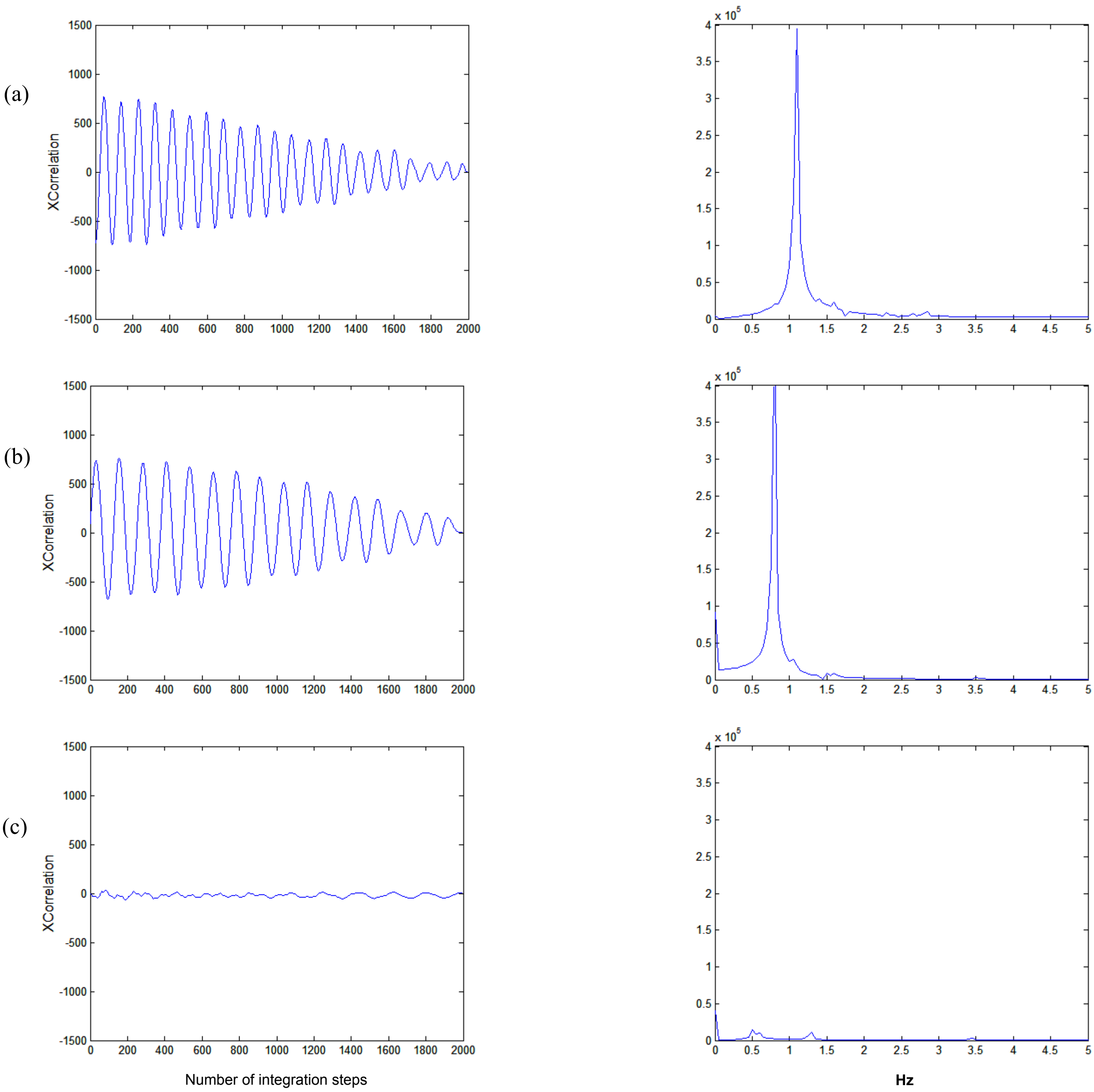

Figure 4. First column: Cross-correlation between sloshing and structural displacement for flexible container with added point masses: (a) 0 kg, (b) 7 kg, (c) 21 kg. Second column: Cross spectrum for the same cases.

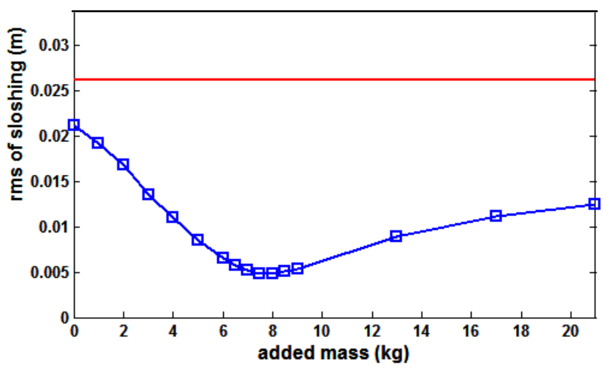

Figure 5. Variation of the rms of sloshing magnitude with mass for rigid ( ) and flexible (□) containers.

References

[1] Anderson, J. G., *Liquid Sloshing in Containers, Its Utilisation and Control*, Ph.D. thesis, Victoria University, Melbourne, Victoria, Australia, 2000.

[2] ANSYS 6.1 Users Manual, ANSYS Inc. Houston, Texas, USA, 2002.

[3] Gradinscak, M., Semercigil, S. E., & Turan, Ö. F., Design of Flexible Containers for Sloshing Control, Proceedings of ASME Fluids Eng. Div. Summer Meeting, Montreal, Canada, Paper No. FEDSM2002-31424, 2002.

[4] Güzel, B. U., Gradinscak, M., Semercigil, S. E., & Turan, Ö. F., Tuning Flexible Containers for Sloshing Control, IMAC XXIII, 2004, Orlando, Florida, USA.

[5] Milne-Thomson, L.M., *Theoretical Hydrodynamics*, 5th ed. Macmillian Press, 1968, 427-442.