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Letter to the Editor

A note on a natural sloshing absorber for vibration control

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1. Introduction

Sloshing of a liquid in a container may be utilized in much the same way as a conventional tuned vibration absorber for structural control. In Fig. 1, a simple mechanical oscillator is shown with lumped mass (m), stiffness (k) and damping (c) elements. The mass accommodates a container partially filled with a liquid, representing the sloshing absorber. Dynamic fluid forces on the container are transmitted to the oscillator to suppress its excessive oscillations. The concept of utilizing a sloshing absorber has been suggested earlier, some successful examples of which are reported in Refs. [1–8].

A sloshing absorber is similar conceptually to a conventional tuned vibration absorber such that the sloshing natural frequency is tuned to a critical frequency of the structure to be controlled. This frequency is normally the fundamental frequency of the structure. The tuning assures the essential strong interaction between the absorber and the structure. A second necessary condition is to provide an energy sink in the absorber to maintain effective attenuations in the structure. This second condition is particularly critical for cases where the disturbance on the structure cannot be represented by a simple harmonic function of constant frequency. Satisfying this second condition is the primary challenge in absorber design for non-harmonic and transient disturbances.

It makes practical sense to select the container parameters of a sloshing absorber to represent storage vessels, since these vessels may already exist as part of the structure to be controlled. However, storage containers generally experience standing sloshing waves due to having comparable liquid depths and lengths. Standing waves are poor energy dissipaters, as compared to travelling waves which result mostly from shallow liquid levels. For this reason, most of the earlier successful attempts deal with travelling sloshing waves [4–6]. Attempts to use deep levels of sloshing liquids are few where Refs. [3,7,8] may represent the most recent contributions in the literature.

A standing-wave absorber requires additional measures to be an effective controller. Earlier observations have shown that strategically placed baffle plates [7,8] enhance the energy dissipation

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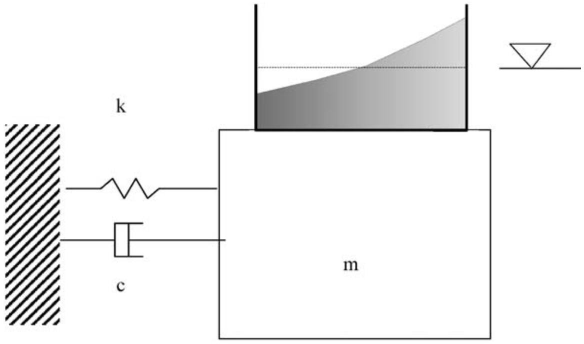

Fig. 1. Showing a single degree-of-freedom oscillator with the sloshing absorber.

due to sloshing. However, performance of the baffles is a strong function of their location relative to the free liquid surface. For a storage container in use, the free surface is expected to change. Therefore, some other means which are less dependent on the level of liquid would be desirable. Such a requirement is the motivation to investigate the sloshing of the raw content of a hen's egg.

An uncooked hen's egg has the very desirable properties of high mechanical damping. This may be easily verified by releasing an egg from a position where its long axis is vertical, and observing how quickly its free oscillations stop. When the very same egg is hard boiled, it requires a significantly longer period to stop from the same starting conditions. This natural phenomenon was first suggested as a possible topic of investigation by J.B. Hunt in 1979 [9] and (despite its everyday familiarity) has not since attracted attention. Results from an experimental study to investigate sloshing in an egg are reported here. The objective is to explore the possibilities of borrowing design features to enhance the effectiveness of sloshing absorbers for structural control.

2. Experiments

Experimental procedure consisted of observing the history of free oscillations of an egg after releasing it from an upright position. As soon as an egg was released from the statically unstable position shown in Fig. 2, with $\theta = 90^\circ$, it immediately attempted to reach the lowest potential energy position corresponding to $\theta = 0^\circ$. Between $\theta = 90^\circ$ and $\theta = 0^\circ$, the egg rocked back and forth as its total available energy oscillated between kinetic energy (due to inertia) and potential energy (due to gravitational pull). Oscillations eventually stopped as the total energy is dissipated. Contact friction and dissipation due to sloshing of the liquid content were the only two sources of energy dissipation.

A cradle was formed to confine the oscillations of the egg in one plane by fixing two plastic compact disk cases on a flat surface with a 17 mm gap between them. The cradle also helped minimize the contact friction effect with its hard and smooth edges. Angular oscillations were recorded by using a standard video camera. A digital stopwatch was also included in the picture frame to provide time information. Recorded image was played back frame-by-frame. History of oscillations were obtained by tracking the angular position of a line drawn to mark the long axis of the egg (also shown in Fig. 2).

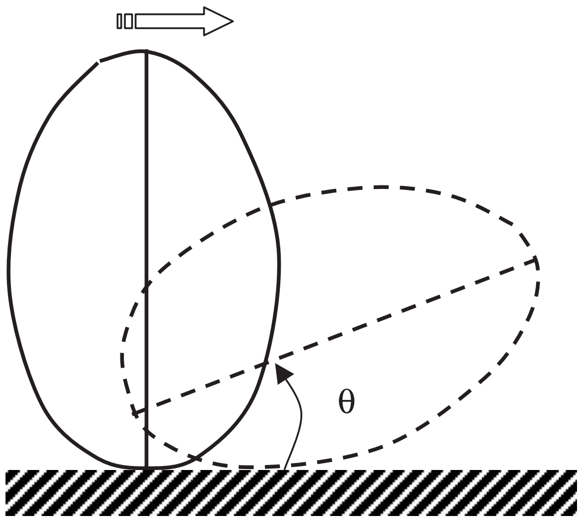

Fig. 2. Illustrating the angular oscillations of an egg.

Care was taken to select the eggs with similar physical properties. All eggs had an approximately 50 ml volume content. Their mass varied between 48 and 52 g. The density of the scrambled liquid content varied by $\pm 4\%$ relative to the density of water. Long axes varied between 57 and 62 mm. Short axes varied between 43 and 44.5 mm.

3. Effect of sloshing

Histories of angular displacement are shown for three different eggs in Fig. 3. These eggs had the aspect ratios of 1.30 (**- - -**, Egg 1), 1.35 (——, Egg 2) and 1.45 (……, Egg 3) between the long and the short axes.

For all three eggs, there is a significant decay in the peak displacement within the first half cycle. This decay corresponds to a big lunge forward (towards right in Fig. 2) and sliding of the point of contact in the opposite direction (towards left). After this first lunge, energy is dissipated in a steady manner until the egg came to a stop.

In Fig. 3, Eggs 1–3 come to a full stop in 3.5, 4.8 and 6.2 s, respectively. The pointiest egg, with the largest aspect ratio, takes the longest time to stop with a natural frequency of approximately 1 Hz, whereas the natural frequency of the other two eggs seem to fluctuate between 1.2 and 1.4 Hz.

In Fig. 4, first 35 s of the displacement history of Egg 2 is shown after hard boiling its contents to make sure that there is no liquid sloshing in the shell. Raw Egg 2 is also repeated in this frame for comparison. Boiled egg has a lower natural frequency of approximately 1 Hz. Energy dissipation capability of the boiled egg is significantly poorer than the case when its content is free to slosh. Solidifying the liquid content of Egg 2 results in taking more than 10 times longer to stop. This significant difference is typical of all the eggs tested in this study. Investigating the important parameters to cause such a difference is the primary objective of the work presented in this paper.

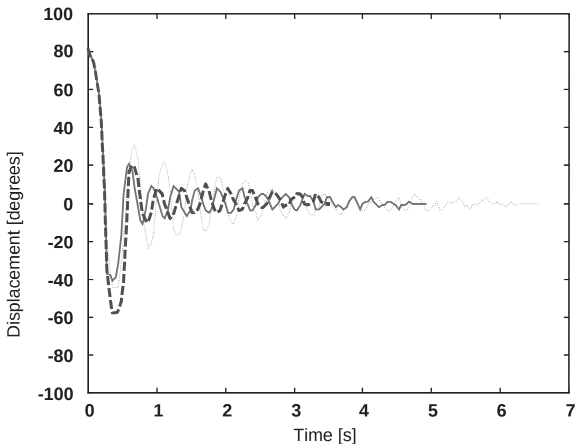

Fig. 3. Displacement histories of three raw eggs with different aspect ratios. (- - -: Egg 1; ——: Egg 2; ……: Egg 3).

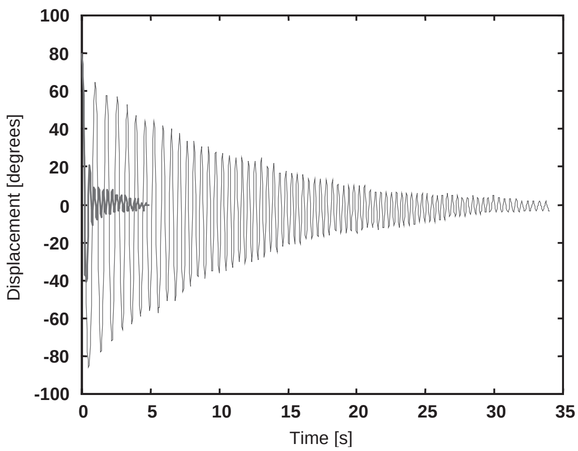

Fig. 4. Displacement histories of Egg 2 before (——) and after (……) hard-boiling it.

4. Effect of separating membranes and volume content

An interesting feature of a raw egg is the fact that the white (albumen) and the yolk are clearly separated with membranes in different compartments as shown in Fig. 5. Hence, the white and yolk have the opportunity to slosh at different phases relative to each other, and relative to the oscillations of the shell. It is quite likely that such a relative motion is important for effective energy dissipation.

Displacement histories presented in Fig. 6 represent the cases when the liquid content of Egg 2 was drained, scrambled and partly reintroduced in the shell. Small holes were made at the two

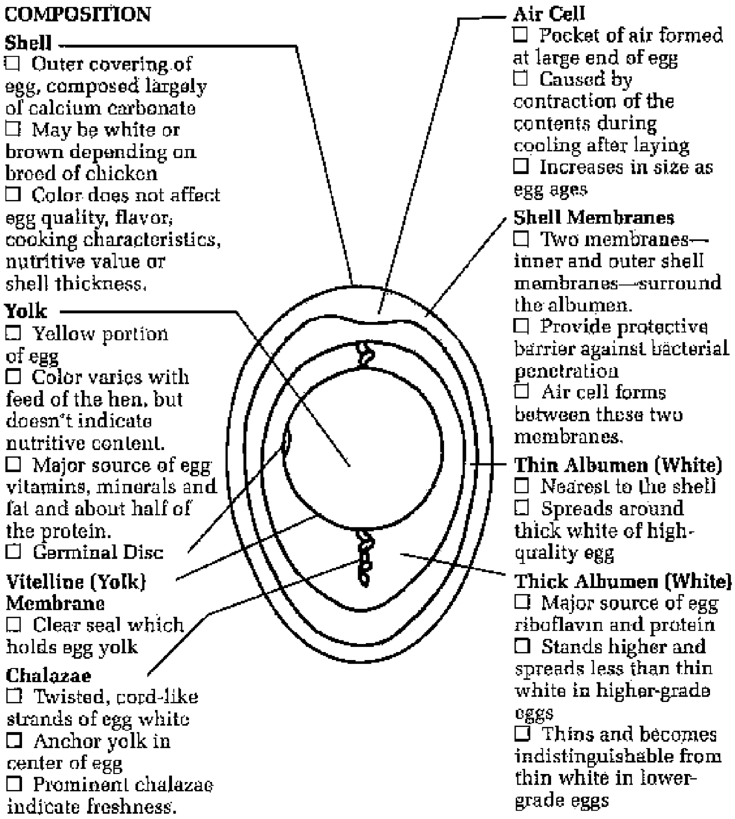

Fig. 5. Showing the composition of an egg from Ref. [10].

opposite pointy ends, membranes were punctured and the content was removed by blowing from one hole. Volume of the removed content was 50 ml. This volume was reintroduced with 10 ml increments using a syringe. Accuracy of volume measurements was ± 2 ml.

For all cases in Fig. 6, oscillations drop below detectable levels between 1 and 2 s, well before that of (approximately 5 s) the case when the membranes separating the contents are in tact. This is quite surprising to indicate that the separation of the white and the yolk is detrimental to the energy dissipation characteristics.

The five frames in Fig. 7 correspond to the case where water was used in place of the scrambled egg content. Results with water as the sloshing liquid are quite comparable to those presented earlier in Fig. 6 with some selective marginal improvements. Angular displacement histories of the raw Egg 2 with its membranes in tact, with its full scrambled content and with water are presented in Fig. 8 for comparison.

A summary of the two experiments with varying sloshing volumes are given in Fig. 9 in the form of 10% settling times. A 10% settling time is defined as the duration required for the displacement magnitudes to decay below 10% of their starting maximum value (of 90°). A short settling time is an indication of effective energy dissipation rate. The vertical axis shows ratio of

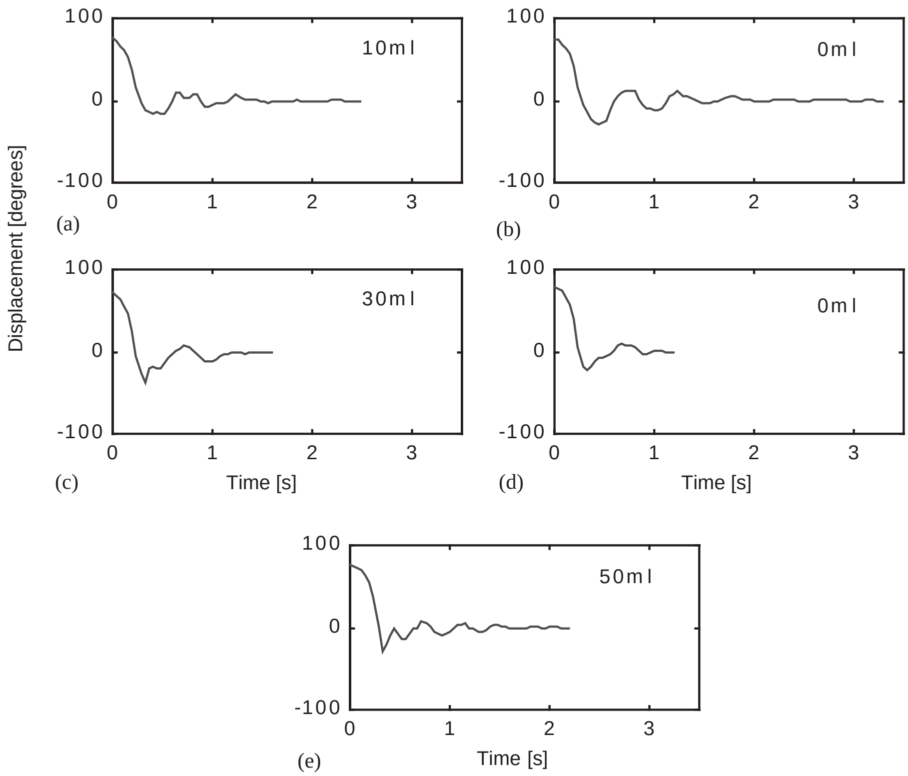

Fig. 6. Displacement histories of Egg 2 when its content was scrambled and put back at volumes of: (a) 10, (b) 20, (c) 30, (d) 40 and (e) 50 ml.

the settling times with different liquid volumes to the settling time measured for the hard-boiled Egg 2. Settling times of the scrambled egg and water content are shown with (○) and (□), respectively. Settling time of the raw egg is 12% of that of the hard-boiled egg. This value of 0.12 is used as the maximum value of the vertical axis.

In Fig. 9, with the exception of 10 ml scrambled content, all cases suggest at least a 95% improvement over the hard-boiled Egg 2. Again with the exception of 10 ml, water seems to perform marginally better than scrambled egg. It is also interesting to notice that the settling time ratio is quite insensitive to the variation of the volume content after 20 ml, indicating comparable decay times for varying volume in absolute sense.

Relative insensitivity to the volume content has two implications. Firstly, large deviations are quite acceptable if the volume content is prescribed to be between 30 and 40 ml (60% and 80% of full capacity) to maintain effectiveness. Secondly, a larger volume content represents a faster rate of energy dissipation in absolute sense. This assertion may be verified by considering that the decay time is quite comparable for varying volume content, and the amount of initial potential energy to be dissipated increases with increasing mass from the same position indicated in Fig. 2. Hence, if a geometry similar to that of an egg is to be used as sloshing absorber, it is advantageous to have its volume content close to a full capacity.

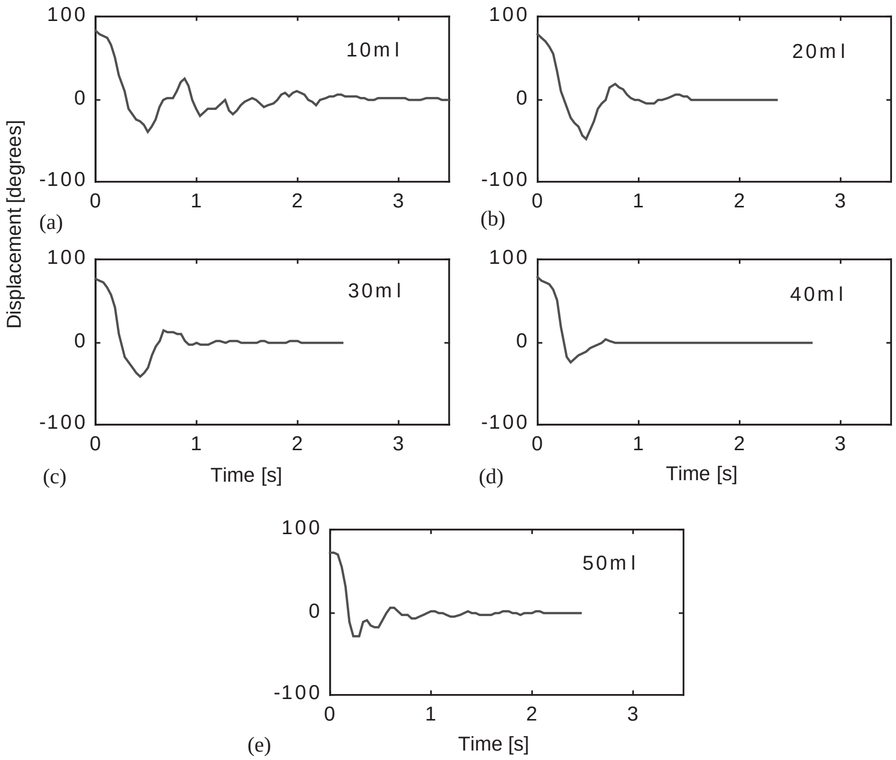

Fig. 7. Same as in Fig. 6 but with water.

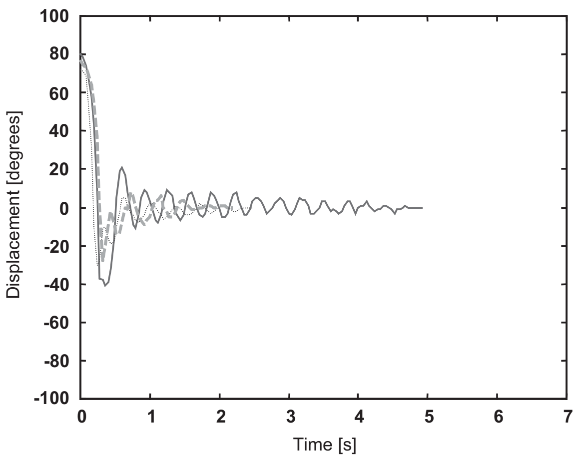

Fig. 8. Displacement histories of Egg 2 with content in tact (——), with content scrambled and reintroduced (- - -), and with content replaced with water (……).

Finally, the settling time ratios of the three eggs discussed earlier in relation to Fig. 3 are given in Fig. 10. Water is used as the sloshing liquid for all three eggs. In Fig. 10, settling time ratios of 0.08 and smaller are possible virtually at all volume contents. The dependence of the settling time ratio to volume content is relatively weak for all three eggs.

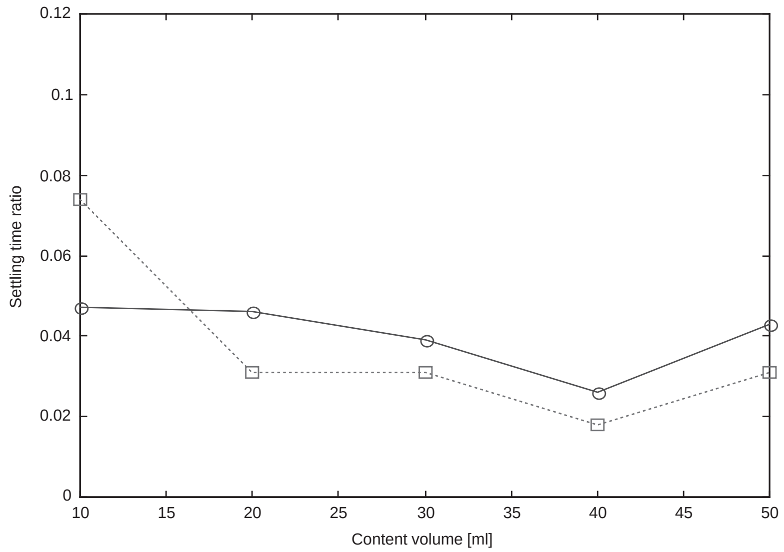

Fig. 9. Variation of the 10% settling time ratios of Egg 2 with volume content.

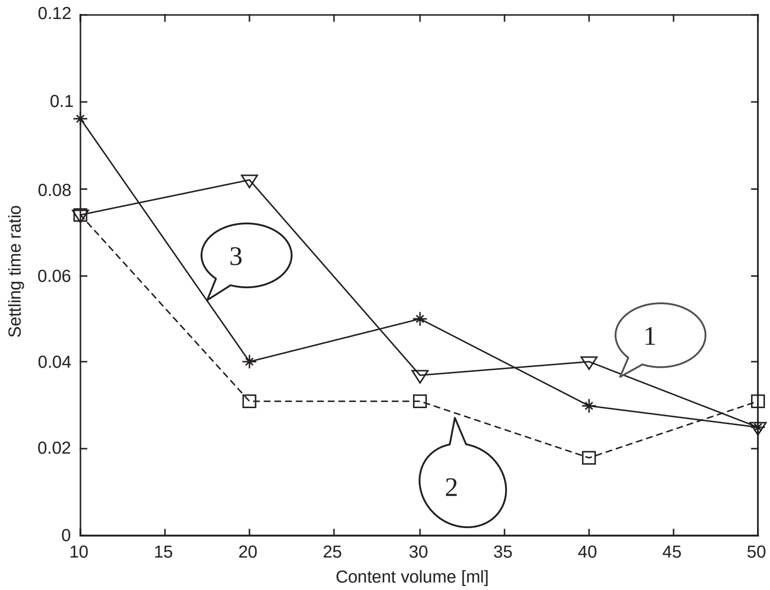

Fig. 10. Variation of the settling time ratio with volume content of water for the three different aspect ratios of 1:1.30; 2:1.35 and 3:1.45.

5. Conclusions

Sloshing of a liquid in a partially full container may be employed to suppress excessive structural vibrations. The basic principle in this application is very similar to that of a conventional tuned vibration absorber.

Representative results from an experimental study are presented in this paper to investigate the possibility of exploiting the efficient energy dissipation mechanism in a raw hen's egg. For efficient energy dissipation, confining the white and the yolk in separate membranes is detrimental. Scrambled liquid content improves energy dissipation. Using water as a sloshing liquid, instead of the scrambled content, may enhance energy dissipation marginally.

The results presented in this paper are of preliminary nature. However, they show every indication that further work is warranted to gain a better understanding.

Acknowledgements

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