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Energy Dissipation through Sloshing in an Egg-Shaped Shell

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Abstract

Sloshing absorbers work on a similar principle to that of tuned vibration absorbers. A sloshing absorber consists of a tank, partially filled with liquid. The absorber is attached to the structure to be controlled, and relies on the structures motion to excite the liquid. Consequently, a sloshing wave is produced at the liquid free surface possessing energy dissipative qualities to suppress excessive vibrations of the structure.

The hen's egg has evolved to dissipate vibration energy rapidly to protect its contents, the embryo. An uncooked hen's egg's capability to rapidly dissipate potentially harmful energy, takes place in the form of sloshing of its contents. Hence, there may be lessons to learn from the **natural** design of an egg which could be employed in the design of a sloshing absorber.

The primary objective of this work is to demonstrate the suitability of the Smoothed Particle Hydrodynamics (SPH) method to numerically model the sloshing dynamics in an egg-shaped shell. Efforts are made to identify the physical events responsible for effective energy dissipation at different fill levels. The possibility of modifying the egg's design to further encourage these patterns is also explored briefly. Although limited space does not allow presentation of these observations, a brief discussion of these cases studies is included.

Introduction

Sloshing is the oscillation of a liquid within a partially full container. In study of sloshing, efforts are usually made to suppress sloshing, due to its damaging effects [4, 15, 16]. On the other hand, sloshing has an inherent ability to dissipate kinetic energy via shearing of the fluid. Hence, liquid sloshing may be employed as an effective energy sink to provide protection for structures exposed to excessive levels of vibration [1, 12, 13, 18].

Limited studies on the effect the sloshing absorber's shape has on its control performance have been completed [9]. In the published literature, practical application has mainly been limited to rectangular [8], cylindrical [7] and toroidal shapes [19]. The lack of a comprehensive investigation on the shape of a sloshing absorber was the motivation to study the sloshing of the raw content of a hen's egg in So and Semercigil [17].

Energy dissipation within a hard-boiled egg is significantly poorer than that in an egg with raw content. This assertion can be easily confirmed by releasing an egg before and after boiling it from a position where its long axis is vertical. Figure 1 includes such an observation as reported in Reference 17. Starting from the same upright position (90°), the hard-boiled egg takes about 10 times longer to come to rest than the case with raw content. The only significant change boiling induces, is to eliminate the sloshing of the liquid content.

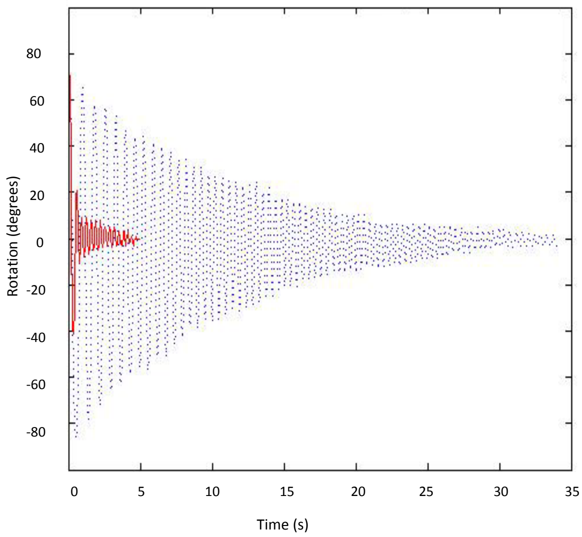

Figure 1. Angular displacement history of an egg when raw (——) and boiled (---), from Reference 17.

In a raw egg, the albumen (white) and yolk are held separate by membranes, as shown in Figure 2(a). The yolk is suspended within the albumen with ties (chalazae). Therefore, yolk and white are able to slosh out of phase from one another, and out of phase from the oscillations of the eggshell. It is possible that this type of relative motion is responsible for the egg's high mechanical damping. However, it is reported in Reference 17 that extracting the content, scrambling, and reintroducing it into the eggshell somewhat improves the energy dissipative characteristics of the egg even further. Such an observation makes the study of the liquid motion inside the egg possible practically. An increase in dissipation has been reported by replacing the scrambled content with water. Another significant observation has to do with the volume content of water inside the egg. Different volume fractions produce comparable stopping times of shell's oscillations. Such an apparent insensitivity to varying liquid levels, is a very desirable characteristic of a sloshing absorber from a design point of view.

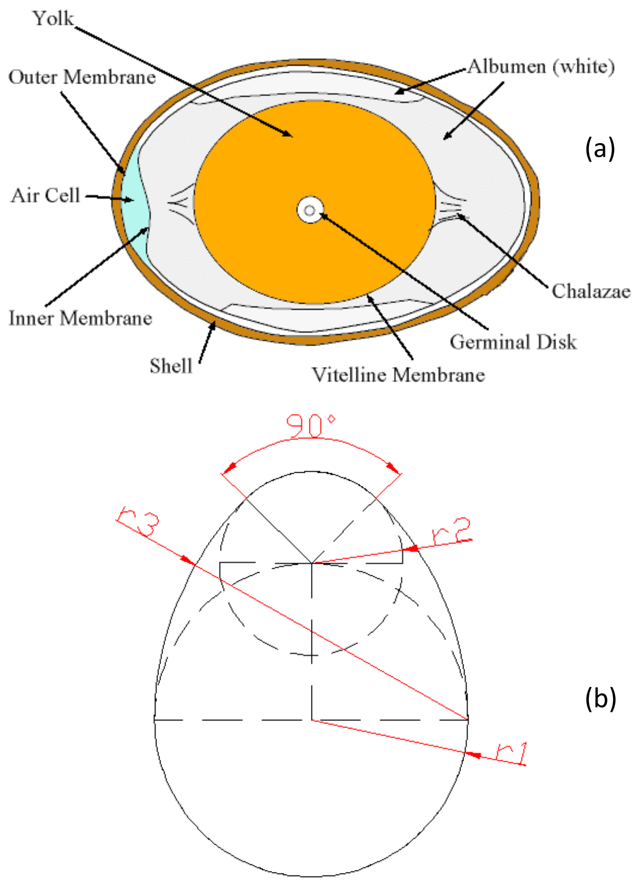

Figure 2. Showing (a) schematic of the physiology of hen's egg from Reference 5, and (b) its geometry from Reference 6 - r1 = 44.5 mm, r2 = 26 mm and r3 = 89 mm, for an aspect ratio of 1.3.

The primary objective of this work is to numerically demonstrate the egg's ability to effectively dissipate energy via sloshing of its liquid content. A grid-free Lagrangian technique, Smoothed Particle Hydrodynamics (SPH) is used to model fluid-structure interaction between an egg-shaped cylinder and the surface on which the egg oscillates. Efforts are to identify dissipation mechanisms to understand them, and possibly to apply them in the design of sloshing vibration absorbers.

Numerical Model

Smoothed Particle Hydrodynamics (SPH) has significant advantages to predict free surface flows as compared to most grid-based conventional computational fluid dynamic techniques. CSIRO's (Commonwealth Scientific and Industrial Research Organisation) Mathematics, Informatics and Statistics Division have developed the code used here. A broad range of complex industrial and environmental fluid flow problems have been modelled successfully with this code [3], and a detailed description of the method can be found in [14]. Hence, SPH is ideally suited to study the fluid-structure interactions in geometries of interest in this study. However, current modelling attempts had to be limited to two dimensions (2D), due to prohibitive computational requirements of three-dimensional predictions. It is anticipated that ever-increasing computing capacities should soon remove such constraints.

The cross-section of the egg-shaped cylinder is shown in Figure 2(b). The sloshing fluid within the 2D eggshell is water with a density of 1000 kg/m^3 and dynamic viscosity of 0.001 Pa s. A particle size of 0.4 mm by 0.4 mm is used to model the shell, water and the flat surface on which the shell oscillates. No-slip condition is used at the inner walls of the shell. Time stepping is explicit, limited by the Courant condition modified for the presence of viscosity [14], and is bounded by 0.31μs, corresponding to around 3.8 million integration steps per period of eggshell's oscillation.

The eggshell is put in an upright position and held for one second so that the water particles reach an initial state of rest. The egg is then released and allowed to respond (roll) dynamically, eventually coming to rest horizontally, at the position of lowest potential energy. Friction between the shell and the surface is set to zero, so that energy dissipation is via the working fluid only.

Numerical Predictions

The predicted displacement histories of the eggshell with volume fractions of 0.2, 0.4, 0.6, 0.8 and 1.0 are shown in Figures 3(a) to 3(e). The eggshell requires around 7.5 s for a volume fraction of 0.2, around 6 s for volume fractions of 0.4, 0.6 and 0.8, and about 5s for a volume fraction of 1.0 to come to rest. Hence, there is an improvement of rate of energy dissipation with increasing volume fraction. However, this change is quite gradual and the egg seems to be relatively insensitive to the amount of fluid within. This predicted behaviour agrees well with that reported in [17].

The nature of free surface flow changes quite drastically with volume fraction. At low volume fractions, large free surface deformations are observed. Snapshots of some instants of interest with the lowest volume fraction of 0.2, are shown in Figures 4(a) to 4(d). The colour scale indicates the maximum velocity of 0.4 m/s in red. Fluid behaviour is highly energetic. Travelling and breaking waves are generated easily, and their inherent steep velocity gradients are responsible for dissipating energy [2, 10, 18]. This behaviour is predicted for even small surface deformations such as that shown in Figure 4(d) which occurs during the sixth cycle of oscillation.

Snapshots of some selective instants when the egg is filled to the highest volume fraction of 1.0 (an air pocket indicated in Figure 2 is always maintained), are shown in Figures 4(e) to 4(h). Minimal free surface, restricts surface deformations and prevents the formation of travelling waves. In contrast to the case of the 0.2 volume fraction, a relatively uniform velocity field is predicted throughout the fluid volume.

The lack of energetic free surface behaviour indicates that the egg is highly reliant on shearing at the inside surface of the shell to dissipate energy. This shearing occurs due to the no-slip condition at the walls. For the higher volume fractions, the egg clearly possesses more initial potential energy as both the fluid mass and the centre of gravity increase at the instant of release. Therefore, coming to a stop over a comparable duration with those of lower volumes, indicates a higher rate of energy dissipation for a higher liquid volume. Shearing at the walls of the shell is, therefore, more important than energetic free surface behaviour for producing high mechanical damping.

Having gained some confidence with the numerical predictions, the possibility of improving the design of the eggshell, is explored next. This modification is introduced in the form of a fin, protruding from the bottom of the egg and extending along its long axis of symmetry, with fin heights of 0.2 to 0.6 of the long axis.

In all the trials with the modified egg, dissipation performance deteriorates with increasing fin height and increasing volume fraction of content. For small volume fractions, an energetic free surface behaviour is observed, similar to that of a no-fin case. Hence, the disturbance caused by the presence of the fin is minimal. As volume fraction increases (as the mechanism for energy dissipation changes from free surface motion to shearing at the boundary), however, the presence of the fin causes fluid to stagnate in small compartments. As a result, shear stress is restricted, deteriorating the rate of dissipation. The level of deterioration, seems to worsen with longer fins. The best performance is always observed with the natural egg. Details of these case studies may be found in [11].

Conclusions

A summary of numerical case studies is presented in this paper to provide some insight into the ways in which rapid energy dissipation takes place in a raw egg. Modelling with SPH provides details which are not possible by experimental observations. It has been observed that the flow pattern within the egg is dependent on volume fraction of its liquid content. At low volume fractions, large free surface deformations dissipate energy, in the form of breaking travelling waves. Dissipative nature of the breaking waves is supported with earlier findings in the literature. At high volume fractions, on the other hand, free surface is calm. Shearing at the shell walls, is the primary mechanism of energy dissipation. It is also observed that the transient response of the egg is relatively insensitive to its volume fraction of fill. This very critical trend agrees well with earlier experimental work.

Limited attempts to structurally modify the internal profile of the egg, result in no positive improvement. However, there may be opportunities to increase the size of the shell, to enhance its performance in absolute sense. Finally, simple experiments (not given here, due to space limitations) suggest that the accuracy of the numerically predicted energy dissipation is certainly acceptable.

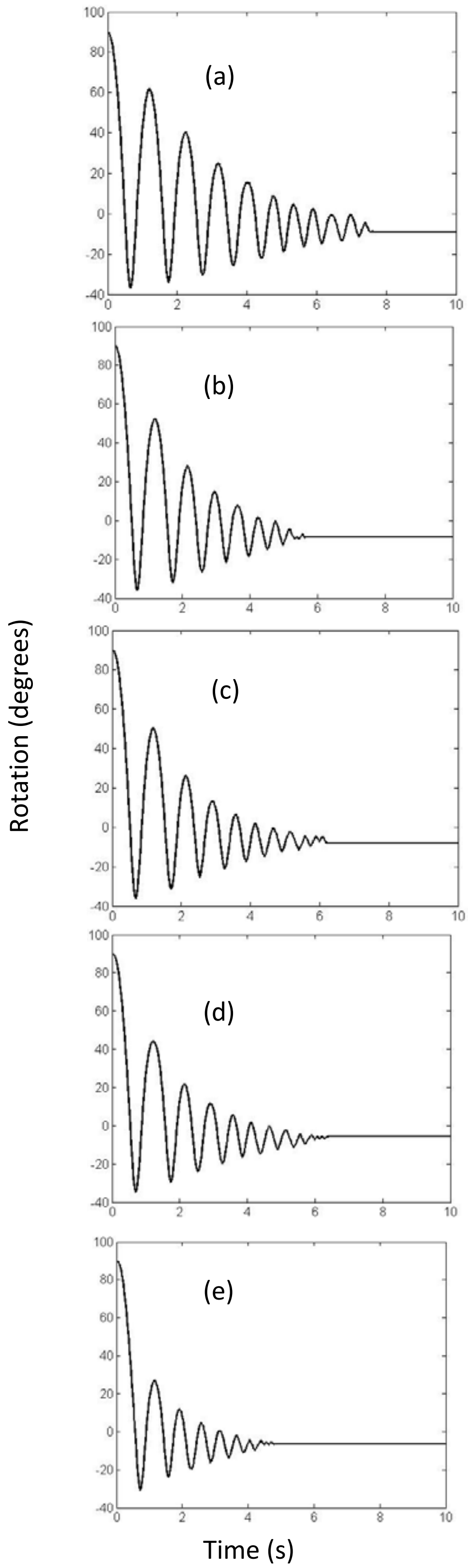

Figure 3. SPH predicted displacement histories with volume fractions of (a) 0.2, (b) 0.4, (c) 0.6, (d) 0.8 and (e) 1.0.

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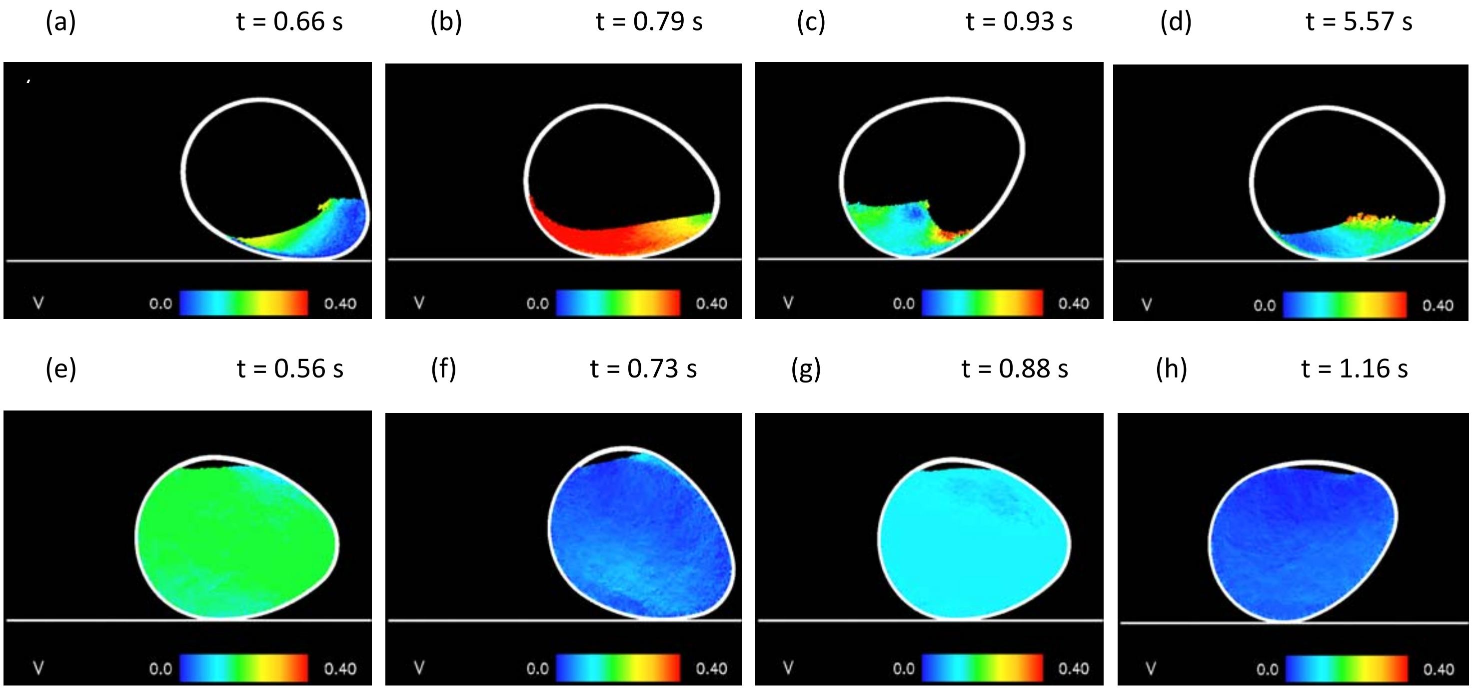

Figure 4. Snapshots of SPH predictions (a) to (d) for volume fraction of 0.2 and (e) to (f) for volume fraction of 1.0.

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