Sloshing Analysis of Baffled Container Using SPH Method

Alireza Kermani and Nagi Elabbasi

Veryst Engineering

***Abstract**: We used the smoothed particle hydrodynamics (SPH) approach in Abaqus/Explicit to simulate sloshing of a partially filled container for a consumer product application. Due to violent sloshing, we did not use conventional methods such as Volume of Fluid (VoF), which is suitable for less extreme deformation of fluid. We investigated the effect of fill level and acceleration on sloshing. Our results indicate that, under severe impact conditions, the maximum sloshing forces are proportional to the mass of fluid and do not scale with acceleration. We also compared the response of the containers with and without baffles. We showed that the container we considered with conventional baffles experiences the lowest maximum stress during sloshing.*

***Keywords**: Smoothed particle hydrodynamics, sloshing, baffles, impact*

1. Introduction

Sloshing, is not unique to consumer product applications. It is also common to the aerospace, naval, and automotive industries. When partially filled liquid containers are subjected to impact, or a similar sudden change in acceleration, the resulting sloshing fluid motion will significantly affect the container's dynamic response. To suppress sloshing effect in containers, structural/geometrical features, such as baffles are commonly used. Baffles also enhance integrity of containers.

Sloshing motion is highly nonlinear and chaotic, and is difficult to study with conventional finite element or finite volume methods, especially when it involves significant deformations, wave breaking, and impact between the fluid and the solid container. But the significant deformation and wave breaking during sloshing can be captured with Smoothed particle hydrodynamic (SPH), which is based on dividing the fluid into set of discrete elements referred to as particles. We use the SPH method instead of the more commonly used Volume of Fluid (VoF) method for multiphase fluid flow due to significant sloshing in this study. The SPH method is a good design tool for analyzing the effect of baffles and other wave-breaking designs intended to limit the effect of liquid sloshing.

We use the SPH method to compare the response of a container with and without fluid due to sudden acceleration. We also investigate several parameters that affect sloshing such as acceleration, fill level (*) and geometrical features. To explore the effect of acceleration we consider two deceleration magnitudes of 0.76g and 0.38g, which stop the container moving at 7.5 m/s in 0.1 and 0.2 seconds, respectively. To explore the effect of fill level, we analyzed two different fill levels of (40%), and (63%). To investigate effect of geometrical features, we compared containers with different baffle configurations.

(*) Fill level is defined as the ratio of fill height from the bottom of the container to the container diameter.

Section 2 describes geometry of the model and its setup. Section 3 illustrates the importance of accounting for sloshing behavior for a partially filled container. Section 4 presents the effect of deceleration magnitude. Section 5 discusses the effect of fill level. Sections 6 investigates the effect of different baffle configurations.

2. Model Geometry and Setup

We set up a simulation of a partially filled container using SPH in Abaqus/Explicit 6.14-2.

The container we modeled is supported at two locations as highlighted in Figure 1. The length of the container is 48cm and its diameter is 20cm, and it is filled with water. It is initially moving along its longitudinal axis and undergoes a deceleration that brings it to a stop. We used 370000 SPH elements for the fluid, and set up contact conditions between the fluid and the walls of the container. Simulation time was 36 hours running on 4 Xeon(R) CPUs E5-1650 with a clock speed of 3.2GHz.

We report the longitudinal reaction force at the container support, maximum stress in the container and roll moment. Roll moment is the moment at the container supports, which is calculated about the axis perpendicular to the longitudinal direction and the direction of gravity. All forces, moments, and stresses reported in the paper are passed through a Butterworth low pass filter with a cut-off frequency of 20Hz, in order to eliminate noise and high frequency content.

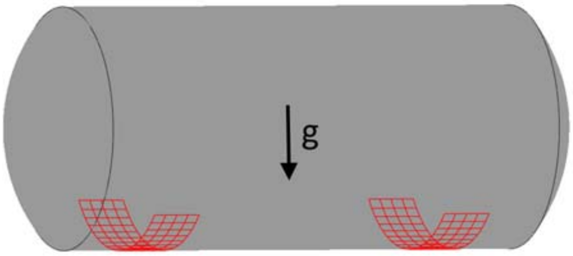

Figure 1. Geometry and boundary conditions. Areas highlighted in red are the supports, arrow g shows the direction of gravity

3. Sloshing Response

The first sloshing model we present involves the container shown above with the fill level of 63% and a longitudinal deceleration magnitude of 0.76g, where g is the gravitational acceleration. We report acceleration in terms of “g” rather than SI values since this is common in sloshing applications. Figure 2 shows wave breaking during sloshing; the left figure is an early stage of sloshing when a wave starts to break: the right figure is a later stage of the wave breaking.

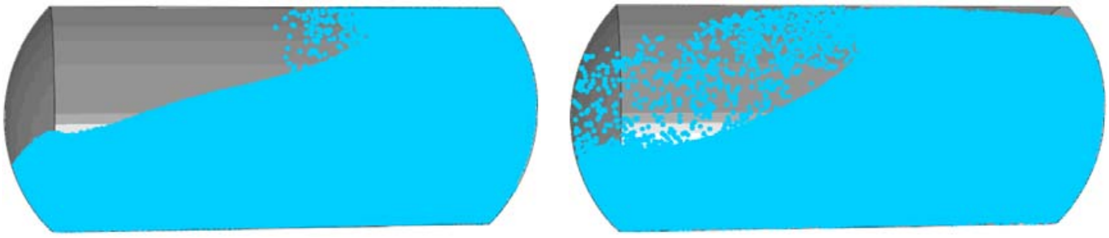

Figure 2. Sloshing in a container at 63% fill level: after 270 ms (left), and after 370 ms (right)

Figure 3 shows the longitudinal reaction force due to sloshing. Longitudinal reaction force is the sum of longitudinal reaction forces at the container supports. The reaction force is normalized by the maximum longitudinal reaction force from a similar simulation of an empty container.

Liquid sloshing increases the reaction force. Note that for this problem the mass of the liquid is 7.3 times that of the container, but the longitudinal reaction force increases less than three times. Although the liquid mass increases reaction forces, simply adding the weight of the liquid to a container structural analysis would dramatically overestimate the resulting reaction force.

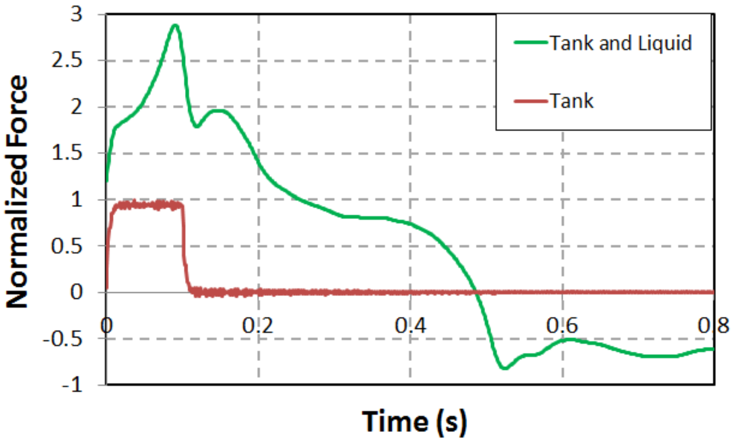

Figure 3. Longitudinal force on the container with and without liquid

4. Effect of Deceleration Magnitude on Sloshing

We assessed effects of deceleration on sloshing by comparing two containers without baffles, with a fill level of 0.63, and with two different declaration magnitudes. Declaration magnitudes are 0.38g and 0.76g, which stop the containers in 0.2 and 0.1 seconds, respectively.

Figure 4 compares longitudinal reaction force and roll moment for the two containers. Force and moment are normalized to their own maximum values. Force and moment of both containers reach their peak values at 0.1s and 0.2s when the containers stops. Although deceleration magnitude is increased 100% from 0.38g to 0.76g, maximum longitudinal reaction force and rolling moment increased only 13%. Therefore, longitudinal reaction force and rolling moment do not scale proportionally with deceleration magnitude.

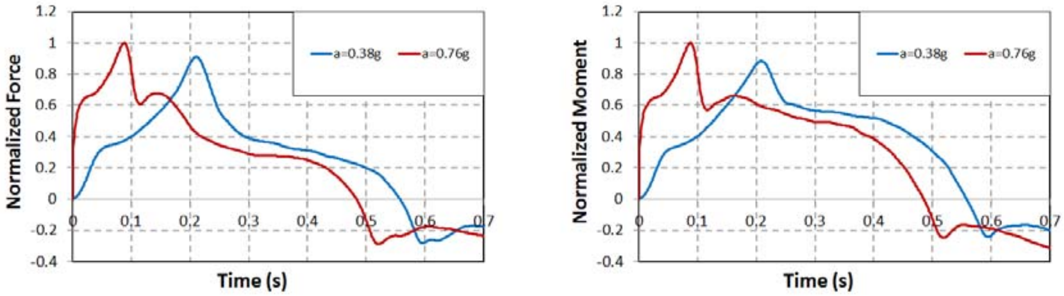

Figure 4. Normalized reaction force (left) and moment (right) due to different decelerations

5. Effect of Fluid Fill Level on Sloshing

We evaluated the effect of fill level by comparing two containers without baffle with different fill levels of 0.4 and 0.63. Both containers are stopped at 0.1 seconds with deceleration magnitude of 0.76g. Note that the mass of the container with fill level of 0.4 is 61% of the mass of the container with fill level 0.63.

Figure 5 compares longitudinal reaction force and rolling moment normalized to the maximum values. The maximum force for the container with a fill level of 0.4 is about 60% of the maximum force value for the container with fill level of 0.63. The maximum moment for the container with a fill level of 0.4 is about 57% of the maximum moment for the container with fill level of 0.63. The reaction force and rolling moment therefore scale proportionally with the mass of the system in our study.

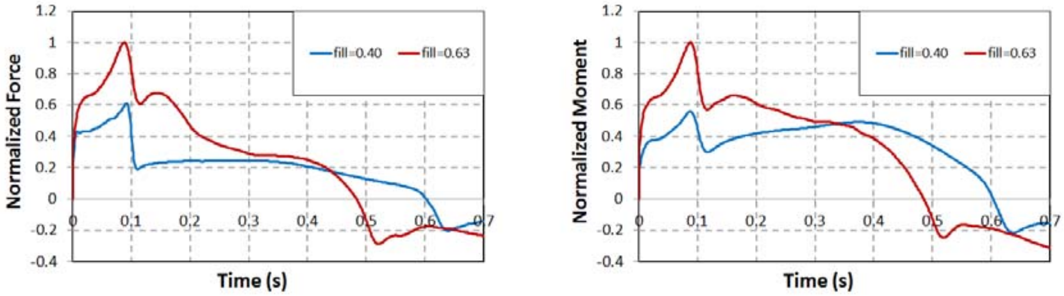

Figure 5. Normalized force (left) and moment (right) at the supports due to different fill levels

6. Effect of Baffles on Sloshing

Baffles are known to suppress fluid sloshing. Their performance depends upon the number, location, and shape of baffles, as well as the fluid mass and acceleration. Kandasamy et al. 2010 investigated the performance of tanks with conventional and alternating baffles using Computational Fluid Dynamics (CFD), specifically a VoF approach. Modaressi-Tehrani et al. 2007 used a CFD technique as well to study sloshing in full-size cylindrical baffled tanks and showed that the maximum longitudinal force depends on baffle designs. CFD methods are well suited for less violent sloshing motions compared to the ones we present in this report.

The effectiveness of baffles was also studied experimentally in small sizes tanks (Lloyd et al. 2002, Guorong et al. 2009, Younes et al. 2007). Sloshing in these studies is due to harmonic or single-cycle sinusoidal motion and therefore does not directly apply to the study of sloshing due to an impact or severe braking.

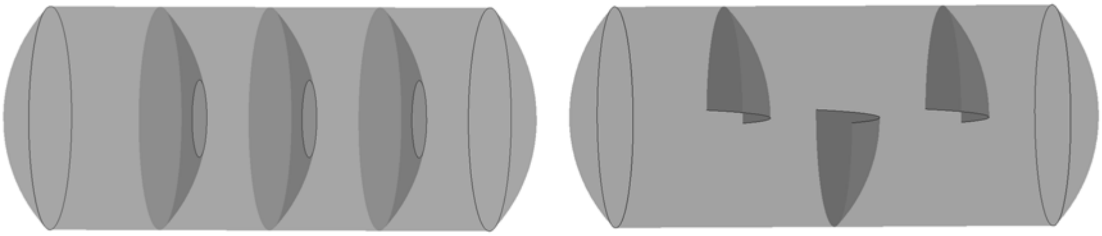

Figure 6. Baffle designs analyzed: Conventional baffle design (left), alternating baffle design (right)

In this study we simulated conventional and alternating baffles to explore their effectiveness in reducing sloshing due to sudden deceleration. We tested three conventional and three alternating baffles that are equally spaced along the length of the container. Their geometries are shown in Figure 6. Curvature of the baffles is identical to the curvature of container head. Conventional baffles have central opening with an area that is 12% of the total container cross section. Alternating baffles are partial baffle arranged in an alternating pattern (see Figure 6, Right).

6.1 Effect of Baffles on the Maximum Reaction Force and Roll Moment during Sloshing

Figure 7 shows sloshing pattern and wave breaking in both baffled containers. Alternate and conventional baffles suppress sloshing differently. Fluid flows through the opening in the conventional baffles. Fluid flows through the staggered openings above/below the alternating baffles.

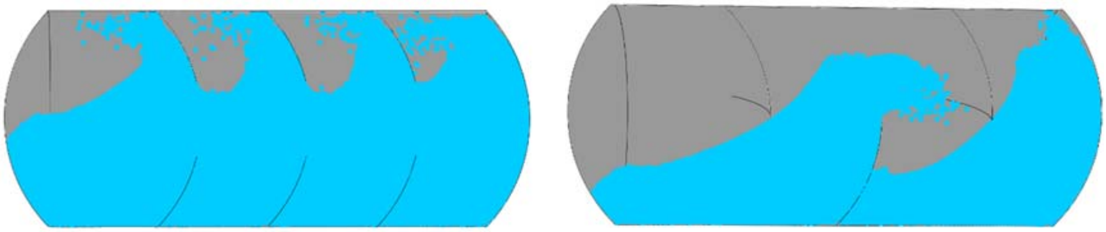

Figure 7. Sloshing in containers with conventional baffle (Left) and alternating baffle (Right)

Figure 8 compares the longitudinal reaction force and roll moment of a container without baffle with containers with conventional and alternating baffles. For this comparison, we considered two cases where the fill levels and longitudinal deceleration magnitudes are different:

  - Fill level of 63% and stopping time of 0.1 seconds, longitudinal deceleration magnitude of 0.76g
  - Fill level of 40% and stopping time of 0.2 seconds, longitudinal deceleration magnitude of 0.38g

Figure 8 shows that baffled containers have lower maximum reaction force and roll moment than the container without baffles, after the containers stop moving (after 0.1 seconds in Figure 8(Top) and 0.2 seconds in Figure 8(Bottom)). Therefore, baffles suppress the sloshing, which reduces the moment and force exerted by the fluid on the container during sloshing. The effectiveness of baffles in suppressing sloshing is widely known and is reported in previous studies such as Kandasamy et al. 2010.

If we focus on the initial stage of the simulation when the container is still moving we see from Figure 8 that baffles do not reduce the initial peak magnitudes of lateral sloshing force and rolling moment during that initial stage. Indeed baffles are increasing the reaction force in the initial stage of sloshing. Previous studies such as Kandasamy et al. 2010 reached a different conclusion. They showed that baffles reduce initial reaction forces in partly filled tank trucks. The severe deceleration and the violent sloshing in this study compared to moderate sloshing in previous studies may be the source of this contradiction.

The baffles change the sloshing flow as evident in Figures 2 and 7. They provide more surfaces that obstruct the fluid flow resulting in a faster deceleration of the fluid (in the initial stage of sloshing) compared to a container without baffles. The surfaces that obstruct the fluid flow are

- The container head in the container without baffle (Figure 2).
- The container head and one of the three alternating baffles together in the container with alternating baffles (Figure 7, Right).
- The container head and three conventional baffles together in the container with conventional baffles (Figure 7, Left).

Therefore the containers with baffles, which provide more surfaces to obstruct, have higher initial reaction force than the container without baffles. The container with conventional baffles provides the most obstructing surfaces and has the highest initial longitudinal reaction force.

The initial reaction moments are not affected in the same way because the volumes of liquid accumulated behind the baffles and the tank head are different in each case. Therefore the difference in the magnitudes of the roll moments is less than difference in the magnitudes of the reaction forces between the containers.

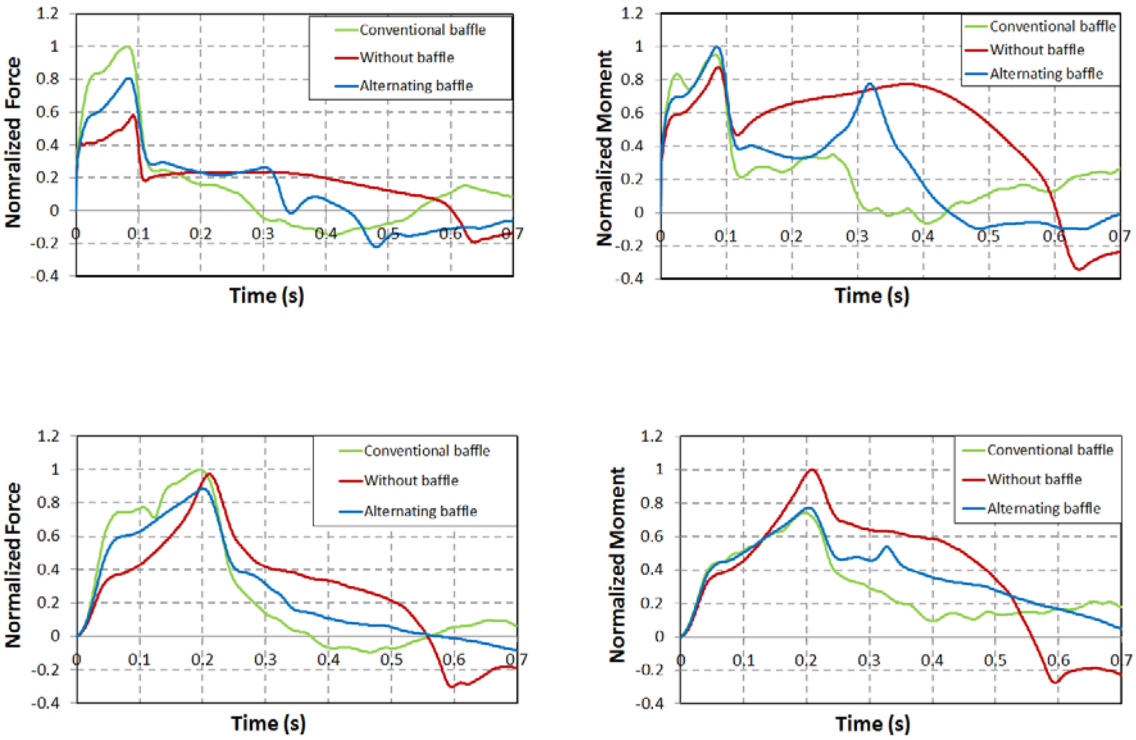

Figure 8. Normalized force and moment. Top: Fill level 40%, a=-0.76g. Bottom: Fill level 63%, a=-0.38g.

6.2 Effect of Baffles on Stresses in the Containers during Sloshing

Usually baffles diminish the maximum stress due to sloshing in a container by suppressing inertia of the fluid in the container. Figure 9 compares the normalized maximum stress induced in the containers during sloshing under the conditions mentioned above. The container with the conventional baffles yields lower maximum stress, despite having the highest longitudinal reaction force. Consequently this container is less likely to be damaged during sloshing.

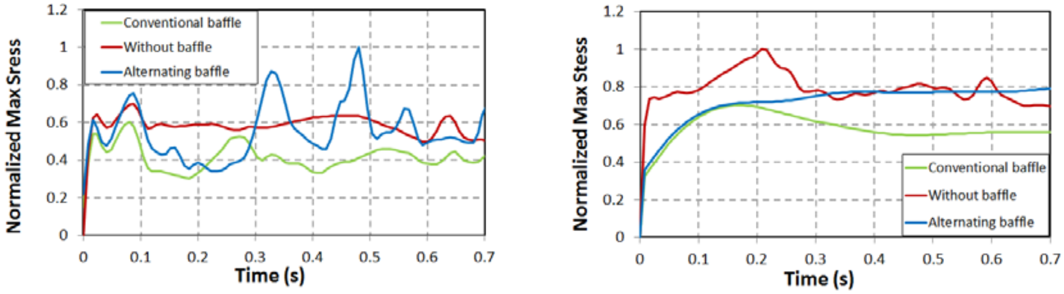

Figure 9. Normalized Maximum stress. Left: fill level of 40% and, a=-0.76g. Right: fill level of 63% and, a=-0.38g

7. Conclusions

We used SPH method instead of the more common VoF method. Therefore we could simulate significant sloshing and wave breaking, which could not be accurately simulated with the VoF method. We showed that sloshing affects roll moment and reaction force in the container, and that the approximate method of adding the fluid mass to standard structural impact analysis does not reasonably predict the effect of sloshing. We also demonstrated that the maximum values of the longitudinal reaction force and roll moment due to sloshing, for the container geometry we modeled, are proportional to the mass of the fluid and do not scale with the deceleration magnitudes we considered. We investigated the effect of alternating and conventional baffles. For the geometry we considered, baffled containers had higher initial reaction force than containers without baffle. The container with conventional baffles had the lowest maximum stress.

8. References

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