Numerical studies on fluid-structure interaction of a liquid-filled tank with baffles

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Abstract. CFD is used to simulate liquid sloshing which affects the safety of baffles in this study, a three-dimensional model of a tank is established. The fluid-structure interaction method is applied to analyze the liquid sloshing phenomenon, deformation and stress of baffles during the acceleration. The distribution of liquid phase in a tank with 0.5 and 0.8 liquid filling ratios are studied. Force distribution of the baffles at different times under 0.8 liquid filling ratio is researched to obtain deformation and stress of baffles under this condition. The simulation results show that the liquid distribution in a tank with 0.8 liquid filling ratio is more stable than that with 0.5. During the acceleration process of the tank with 0.8 liquid filling ratio, the deformation and stress of the baffles are inversely proportional. The roots of baffles suffer from large stress, which is easy to crack under certain conditions. It should take protective measures at the root of the baffles to avoid cracking.

1. Introduction

Liquid sloshing is a common phenomenon in partially filled containers, such as space vehicles, aircrafts, cargo tanks, which might lead to large deformation or even damage to containers [1]. When the frequency of the external excitation is close to the natural frequency of the fluid in the tank or the amplitude of the excitation is very large, a violent oscillation may occur and large impact pressure on the tank can lead to the damage of structures.

Many general problems of battles and liquid sloshing in a tank have been studied [2-6]. C.Hermange [7] studied a 3D SPH–FE coupling for FSI problems, sloshing tank interactions with an elastic beam in shallow oil was investigated numerically and experimentally. S. Nicolici [8] used Ansys Workbench to study the fluid–structure interaction (FSI) in partially filled liquid containers, the interaction liquid–structure is modeled considering full and one-way coupling. Liu Xiaomin [9] studied the effects of different battle materials and different filling rations on the force which is exerted on the baffles and the tank wall with two-way fluid structure interaction. Laura Battaglia [10] studied numerical and experimental studies of three-dimensional (3D) sloshing problems. Free surface evolution measurements were used to validate the numerical method. Ning Kang [11] studied the influence of baffle position on liquid sloshing during the braking and turning of a tank truck using a volume of fluid (VOF) model.
The safety of containers is a common considerable problem, baffles attacked by liquid sloshing in tanks need more research. The fluid–structure interaction (FSI) in partially filled liquid containers is investigated in this paper, interaction between fluids (water and air) and baffles is modelled considering one-way coupling.

2. Model setting

2.1. Physical model
The geometric model of a tank with three baffles is shown in Figure 1. The length of the horizontal cylindrical tank along the Y axis is 5.776m and the diameter is 2.525m. Three baffles are parallel to the Z axis. The upper end of the baffle is 0.982m from nearby vertical tank wall, the lower end is 0.545m, thickness of baffles is 3mm. Each baffle is divided into 4 small pieces, and the distance between each piece is 5mm.

![Figure 1. The geometric model of the horizontal cylindrical tank with three baffles](image1)

2.2. Mesh model
The meshes of the fluid domain and the solid domain are shown in Figure 2. The fluid domain is divided by a tetrahedral mesh, number is about two million. The solid domain is divided by sweep, it is three layers, the number is about 0.1 million. The independence of mesh is verified.

![Figure 2. The mesh of the fluid domain and the solid domain](image2)

2.3. Solution setting
The transient calculation of the fluid domain, gravity is the positive direction of the X axis. VOF model is applied, air as the first phase. Loading the source term with the Y-axis acceleration of 5m/s², turbulence model is Realisable k-ε, the SIMPLE algorithm for the velocity-pressure coupling term, and the pressure in the discrete format is PRESTO. Time step is 0.001s, calculation ends in 2.5s. The material of the baffles in the structural domain is steel, liquid sloshing produces a load impact on the tank wall and baffles, pressure of the fluid-solid coupling surface is extracted, fluid and solid zones are
connected through system coupling. The pressure of interaction surfaces in the fluid domain is imported to the solid coupling surface, deformation and stress of baffles are calculated over time [9].

3. Results and discussion

3.1. Liquid sloshing with 0.5 and 0.8 filling ratio of a tank

Liquid sloshing of 0.5 and 0.8 liquid filling ratio of a tank are simulated. Phase distributions of air and water at the initial, 0.5s, 1s, 1.5s, 2s, and 2.5s are shown in Figure 3. After the acceleration source is loaded, fluid in the cylindrical tank begin to slosh. Water in the tank with 0.5 liquid filling ratio is in four areas because of three baffles, and the gas distribution of each part is similar at 0.5s. Water at the right end of the tank moves to the top of the tank at 1s, the height of the liquid on the left side of the baffle A is low, and the liquid on the left side of the baffle B and C are analogous. The liquid levels on the left side of the baffle A and B decrease, liquid on the left and right sides of the baffle C increases. At 2s and 2.5s, two sides of the baffle A are filled with air, the baffle C are filled with liquid, which reaches the ceiling of tank. It can be seen that tank with 0.5 liquid filling ratio has large space to slosh. The liquid in the tank with 0.8 filling ratio slosh slowly, air is present on both sides of the three baffles at 0.5s. After 1s, air is being on two sides of the baffle A, and both sides of the baffle B and C are filled with liquid. The sloshing amplitude is small, sloshing state is relatively stable.

3.2. Liquid pressure distribution

The pressure distribution on the XY plane of the tank with 0.8 liquid filling ratio at 2.5s is shown in figure 4. It shows that the liquid pressure of the tank gradually increases along the positive direction of the Y axis, and the liquid pressure distribution on the two sides of the baffle is different. The fluid pressure on the right of three baffles is greater than that on the left.
Figure 4. The pressure distribution on the XY plane of tank with 0.8 liquid filling ratio at 2.5s

Figure 5. The deformation of the three baffles of the tanker with 0.8 liquid filling ratios in the Y axis direction at 2.5s

3.3. The deformation distribution
The deformation of the three baffles of the tank with 0.8 liquid filling ratio in the Y axis direction at 2.5s is shown in figure 5. It shows that the overall deformation of the baffle B is the largest, the 2 # and 3 # block protrudes significantly in the negative direction of the Y axis, the maximum deformation is 9.3271mm, and the deformation of 1 # and 4 # block is relatively small. The four small plates of the baffle C are relatively uniformly deformed, but the deformation is not large. The deformation of the four small plates of the baffle A has a large difference, 1 # block is not deformed, and the deformation of 2#, 3#, and 4 # block is larger than that of the blocks corresponding to the baffle C, but it is smaller than that of the blocks corresponding to the baffle B. From the distribution of the two phase and the pressure inside the tank of 0.8 liquid filling ratio at 2.5s, the 1 # block of the baffle A is filled with air, which is not impacted by water. The gas liquid interfaces are nearer than other baffles, and the deformation is larger than that of baffle C. Both the baffle B and C are filled with liquid, the baffle B is located in the middle, and C is farthest from the air. It can be seen that the deformation of the three baffle corresponds to the force generated by the liquid sloshing.

The deformation distribution of the baffle A, B and C at 2.5s is shown in Figure 6. It shows that the deformation of each middle of baffle is large, and the deformation of baffles near the fixed position of the tank is small. The deformation of the middle 3 # block of each baffle is the largest. The deformation of each baffle B and C are similar. The 1# block of baffle A has no deformation, and the deformation of 3 # block of baffle A is between 3# block of baffle B and C.
3.4. Stress distribution
The stress distribution of baffle A, B and C at 2.5s are shown in figure 7. It can be seen that the stress of the baffles is inversely proportional to the deformation, and the location of stress concentration is near the fixed end. For each block of the baffle, the larger deformation in the middle, the greater stress near the fixed end. Stress at the root of each block is the largest and gradually decreases towards the middle. Stress at the root of the baffle B is greater than that of baffle A and B from overall. In 2.5s, bottom of 4# block of battle C has the smallest stress at 0.7s and 1.2s, which is 34.178MPa, and the highest stress at 1s, which is 40.945MPa.

4. Conclusions
The fluid-structure interaction is applied to analyze the liquid sloshing in a horizontal cylindrical tank, deformation and stress of baffles are also investigated. The results show that:

- Tank with 0.8 liquid filling ratio has less sloshing and more safe operation than that of 0.5 liquid filling ratio. A high liquid filling ratio is recommended to use.
- At different locations of the same baffle, the magnitude of the stress is inversely proportional to the deformation. For different baffles, the deformation is large and the stress is also large from overall. During the manufacturing process, the root of the baffle should be locally strengthened to prevent the problem of baffle cracking during repeated using.

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