Simulation analysis of liquid sloshing under different working conditions of hazardous materials rescue truck

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Abstract. The geometric model is built with SOLIDWORKS, and the VOF (Volume Of Fluid) method in the CFD (Computational Fluid Dynamics) software fluent is used to simulate the sloshing characteristics during the brake and steering of the Hazardous Materials Rescue Truck. The braking acceleration, the liquid filling ratio of the vehicle, lateral acceleration, the effect of the baffle during braking and steering are respectively studied. The results show that the steering and braking of Hazardous Materials Rescue Trucks will cause the liquid in the tank to slosh, and the liquid sloshing will cause the wall slosh force of the tank to change. The driving stability of Hazardous Materials Rescue Trucks can be effectively improved by the reduction of braking force, proper liquid-filling ratio, reduction of lateral acceleration, and increase of baffles.

1. Introduction
Hazardous Materials Rescue Truck is a three-in-one functional integrated body that can collect and transport emergency materials in the form of three kinds of substances: toxic, harmful, flammable, explosive and corrosive liquid, and solid liquid mixtures. Due to the sloshing of liquid vehicle go in the non-full load tank, the dynamic load is changed by steering and braking will affect the driving stability of the tanker [1]. At present, methods for studying liquid sloshing in tanks at home and abroad include quasi-static analysis [2], simulation method [3], equivalent mechanical model [4] and test [5]. Literature [6] studied the effects of different baffles and different filling ratios on the driving stability of tankers during braking. In order to improve the driving stability of Hazardous Materials Rescue Trucks, it is important to study the influence of liquid sloshing on stability during steering and braking. Braking force distribution of front and rear axles.

2. Gathering tank parameters and finite element models

2.1. Gathering tank parameters
As shown in figure 1, the two tanks are placed in the longitudinal direction are filter tanks, and one tank is placed in the lateral direction are collection tanks. In this paper, the liquid sloshing in the collection tanks is studied. The collection tank has a nominal diameter of 1800 mm and the total length of the tank is 4000 mm. The two ends are standard elliptical heads, and the area of the baffle is 1.27 m².
2.2. Finite element models

In the establishment of the finite element model, in order to simplify the calculation of the model, it is necessary to simplify some of the components of the model, ignoring the role of non-bearing small components. Based on the above principles, a tank model is made up of two ellipse head, a cylinder and baffles. Since the thickness of the baffle is small relative to the length of the entire tank, the effect of thickness is ignored during modeling this paper does not consider the influence of the reinforcement rib and the wall thickness of the tank.

As shown in figure 2, The nominal diameter of the tank is 1800 mm, the length of the cylinder is 4000 mm, and the volume of the tank body is 10.04 m$^3$. According to the nominal diameter of the tank, the relevant parameters of the selected elliptical head are calculated: the curved surface height is 450 mm, and the straight edge height is 40 mm. The X-axis positive half-axis is set to the vehicle's forward direction, the Z-axis direction is set to the vehicle's lateral acceleration direction, and the Y-axis is set to perpendicular to the ground. The acceleration of the fluid is applied by defining the momentum source term, and the definition of the momentum source term can be setting by UDF.

The two phases in the tank are water and air, and the density of water is 998.2 kg/m$^3$ and dynamic viscosity is 1.003×10$^{-3}$ kg/(m·s). In this paper, the VOF method is used to solve the instantaneous liquid level during liquid sloshing. Changes are accurately captured by VOF method in gas-liquid two-phase interface, the continuity equation and the momentum conservation equation is considered.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0 \quad (1)$$

Momentum conservation equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] \quad (2)$$
where \( u \) and \( p \) are velocity and pressure, respectively. \( \rho \) and \( \mu \) are the average density and dynamic viscosity based on the volume friction, respectively.

\[
\mu = \mu_w + (1 - \alpha_w) \mu_u \tag{3}
\]

\[
\rho = \rho_w + (1 - \alpha_w) \rho_u \tag{4}
\]

where \( \alpha_w \) is the liquid volume fraction, \( \rho_w \) and \( \rho_u \) are the liquid and gas densities, respectively, and \( \mu_w \) and \( \mu_u \) are the liquid and gas viscosities, respectively.

3. Calculation results and analysis

3.1. Simulation of vehicle steering

In this paper, the liquid-filling ratio is defined as \( K = h/2R \), \( h \) is set to the height of liquid level, \( R \) is set to the tank radius, assuming a liquid-filling ratio of 0.5 and a lateral acceleration of 0.3 \( g \). At the beginning, there is no sloshing on the liquid and the wall surface, as shown in figure 3, at the initial time the tank is divided into two part of the same area, the upper part of the interface is air, the lower part is water.

![Figure 3. Distributions of gas-liquid phase.](image)

3.1.1. Effect of different liquid filling ratio on the force in direction \( z \). The liquid fill level in the tank truck cannot be too high, so it is necessary to reserve certain space. Especially when the dangerous chemicals storage vehicle is studied in this paper transports dangerous chemicals, the liquid is expanded and the temperature is raised by too much solution sloshing, so the liquid fill level needs to be strictly controlled. The tank truck transport volume is usually above half load, so the fill-to-liquid ratio is set to 0.5, 0.6, 0.7, 0.8, 0.9, and lateral acceleration is set to 0.3 \( g \). In figure 4, the abscissa represents simulation time, the ordinate \( F_z \) represents forces in direction \( z \) on tank wall.

As shown in figure 4, when the liquid filling ratio is set to 0.5 to 0.6, the crest value of forces in direction \( z \) becomes larger as the liquid filling ratio increases, and the magnitude of the wall slosh force is mainly affected by the amplitude of the shaking. As shown in table 1, with the increase of liquid-filling ratio, the inertial force gradually increases, and the liquid in the tank will surge forward at a faster speed, and the arrival time of the crest gradually decreases. When the liquid filling ratio is increased from 0.7 to 0.9, the crest value decreases as the liquid filling ratio increases. Because as the liquid-filling ratio increases, the mass ratio of the liquid to the tank gradually increases, and the inertial force plays a leading role. At this time, the liquid sloshing amplitude also decreases. When the liquid filling ratio reaches 0.9, the solution in the tank is close to full load, and the peak value is much lower than the filling ratio of 0.8.
Table 1. First crest value of forces in direction z

| Liquid filling ratio | First crest value (kN) | First crest time (s) |
|----------------------|------------------------|----------------------|
| 0.5                  | 3.148                  | 0.42                 |
| 0.6                  | 3.441                  | 0.38                 |
| 0.7                  | 3.420                  | 0.36                 |
| 0.8                  | 2.846                  | 0.32                 |
| 0.9                  | 1.605                  | 0.22                 |

3.1.2. Influence of lateral acceleration on the force in direction z. The rollover threshold of heavy-duty trucks is 0.4 g~0.6 g [7], and the estimated value is high due to the neglect of the suspension and tire elasticity. Therefore, assuming the upper limit of the study on lateral acceleration is 0.4 g. The lateral accelerations are set to 0.1 g, 0.2 g, 0.3 g and 0.4 g respectively, and the liquid filling ratio was set to 0.5. In figure 5, the abscissa represents simulation time, the ordinate $F_z$ represents forces in direction z on tank wall. The figure 5 show that with the increase of lateral acceleration, the liquid slosh force on the force in direction z become larger and the liquid sloshing is intensified.

3.2. Simulation of vehicle braking

This paper is assumed that the tank truck is driven in the positive direction of x at an initial speed of 80km/h, and apply braking deceleration for 2 s, acceleration is taken as 6 m/s². In figures 6 and 7, the abscissa represents simulation time, the ordinate $F_x$ represents forces in direction x on front head of tank.
After 2 s, the liquid in the tank will oscillate freely under the gravity.

3.2.1. Effect of different braking deceleration on the force in direction x. In this paper, the braking deceleration is set to 5.6 m/s$^2$ to 7.2 m/s$^2$, respectively, with an interval of 0.4 m/s$^2$. To take the braking deceleration 5.6 m/s$^2$ as an example, as shown in figure 6, $F_x$ increases rapidly with the change of time, reaching the maximum value at about 0.8 s. Because when the vehicle starts braking, due to the sudden effect of braking deceleration, the liquid in the tank rapidly oscillates towards the front wall of the tank body under the action of inertial force and impacts the front wall, so that the tank receives a sharply rising $F_x$.

When the $F_x$ reaches the maximum value, $F_x$ gradually decreases with the change of time. Because when the all liquid in the tank moves to the front side of the tank under the action of inertial force, due to the reaction force of the front wall of the tank on the liquid, part of the liquid moves backward, causing the $F_x$ to gradually decrease. At 1.28 s, $F_x$ reaches a trough. From 1.28 s to 2 s, $F_x$ gradually increases with the change of time. Because after the liquid moves to the rear side of the tank, the liquid continues to move forward due to the reaction force of the rear wall of the tank body on the liquid. At 2 s, the force on the front head will drop abruptly, because of the sudden disappearance of the brake deceleration, which causes the inertial force of the liquid applied to the tank to suddenly disappear. Comparing with other braking deceleration in figure 6, as the brake deceleration increases, the crest value of the force at the front head is increased. Therefore, it is recommended that when driving the tank truck, the pedal should be slowly pressed to ensure a small brake deceleration when the vehicle brakes.

![Figure 6. Forces in directions x during braking.](image.jpg)

![Figure 7. Forces in directions x during braking.](image.jpg)

3.2.2. Effect of different liquid filling ratio on the force in direction x. Assuming the vehicle is driven at a constant speed at the initial moment. The liquid ratio is set to 0.5, 0.6, 0.7, 0.8, 0.9 respectively, and the brake deceleration is set to 6 m/s$^2$. As shown in figure 7, when the liquid filling ratio is set to 0.5 to
0.8, the crest value of the force in direction x increases as the liquid filling ratio increases. When the liquid filling ratio is set to 0.9, the liquid in the tank is close to full load, and the liquid sloshing amplitude is extremely small, so the crest value is lower than the filling ratio of 0.8.

3.3. The effect of the number of baffles on the force in direction x

Since the lateral baffle studied in this paper has little effect on the suppression of the liquid slosh force during steering, only the influence of the change in the number of baffles on the braking is considered. Assuming that the vehicle is driven at the initial speed of 80 km/h, the braking deceleration is set to 6 m/s², the number of baffles is 1, 3, 5, 7 and the filling ratio is 0.5 and 0.6 respectively.

As shown in the figure 8, when the number of baffle is one, it is located in the center of the tank. In figure 9, the abscissa represents simulation time, the ordinate Fx represents forces in direction x on front head of tank. The results in figure 9 show that after adding the baffles in the tank, the crest value of the force in direction x at the front head is obviously decreased, and the fluctuation range is more gentle than that without the baffles, which indicates that the addition of the baffles to the liquid in the tank sloshing plays a great role in suppressing. The crest value of slosh force at the front head significantly decreases as the number of baffles increases.

![Baffle distribution](image)

**Figure 8.** Baffle distribution.

![Forces in directions x during braking](image)

**Figure 9.** Forces in directions x during braking. (a) K=0.5 and (b) K=0.6.

4. Conclusions

In this paper, the effects of different braking deceleration, liquid-filling ratio, lateral acceleration and the number of baffles on the driving stability of the vehicle during the steering and braking of Hazardous Materials Rescue Trucks are studied. In summary, the following conclusions are offered:
When Hazardous Materials Rescue Truck is turning, maintaining a high liquid filling ratio and a low steering acceleration is advantageous for reducing the liquid slosh force in the tank.

When Hazardous Materials Rescue Truck is braking, as the braking deceleration increases, the crest value of the slosh force of the front head increases. At a fixed brake deceleration, when the liquid filling ratio is 0.5 to 0.8, the change in the force in direction x of the front head is positively correlated with the change in the liquid filling ratio. When the liquid filling ratio continues to increase, the force in direction x of the front head decreases.

The addition of baffles in the tank has a good effect on suppressing liquid sloshing in the tank. As the number of baffles increases, the driving stability of the vehicle increases significantly.

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