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Bidirectional Fluid-Structure Coupling Simulation Analysis of the Tank Body of A Liquid Tanker under Emergency Braking and Sharp Turning Conditions

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Abstract: Based on the specific structural dimensions of a liquid tanker's tank body, a simplified 3D model of the tank body is constructed. Utilizing the Ansys simulation platform, a bidirectional fluid-structure coupling simulation environment is established. The working condition loads under sudden braking and sharp turns of the liquid tanker are designed, and finite element simulation analysis models under different filling ratios are constructed. By comparing the simulation results, the impact of the liquid inside the tank on the tank body and its patterns under different filling ratios are obtained. The simulation analysis results indicate that the greater the filling ratio of the tank body, the greater the impact stress on the tank body and the wave-proof plate, and the stress is proportional to the filling ratio. Both the stress of the tank body and the wave-proof plate are less than the allowable limit stress of 303 MPa, and both the tank body and the wave-proof plate meet the strength requirements.

1. Introduction

In recent years, China's transportation industry has entered a brilliant development period. Road transportation has become the main body. As one of the most commonly used transportation modes in road transportation, liquid tank trucks are commonly used to transport some liquid cargoes. However, decelerating and turning during the driving process of the tank truck will cause the liquid in the tank to shake. However, due to the flow characteristics of the liquid and the liquid-solid coupling effect between the liquid cargo and the tank wall in the tank car, the safety accidents of the tank car are frequent. The simulation analysis of the violent shaking of the liquid in the tank body and the deformation of the tank structure by using the two-way liquid-solid coupling has a practical significance to ensure the safety of the tank truck in the driving process.

In recent years, a series of advancements have been made in research on liquid sloshing in liquid tanker trucks and its impact on the tank body both domestically and internationally. Wang Yuting[1] employed the fluid-structure interaction method of Fluent simulation software to study the sloshing patterns of liquid inside the tank, exploring the effects of different filling ratios and lateral accelerations on liquid sloshing within the tank. Mao Haijian[2] utilized the fluid calculation software

FLUENT to set varying liquid loading parameters for liquids of different densities inside the tank, analyzing the time-domain response of liquid impact within the tank through fluid-structure interaction to understand the impact characteristics of liquids of different densities. Zhang Tao's[3] computational results showed that the forces on the front head and the first four wave-proof boards of the tank body gradually increased with time during braking, and rapidly decreased after reaching a peak. Unal[4] used the fluid-structure interaction method to study the sloshing suppression effect of T-shaped baffles in rolling tanks, and analyzed the impact of baffle height, filling depth, rotation angle, etc. on liquid sloshing. Strelnikova[5] analyzed the vibration response of rigid cylindrical liquid-filled tanks under vertical and horizontal loads based on fluid-structure interaction, considering the effects of horizontal and vertical baffles and elastic effects, and studied the tank response under free vibration, forced vibration, and parametric vibration.

This article takes the tank body of a certain liquid tanker as the research object, and employs bidirectional fluid-structure coupling to conduct simulation analysis and solution for the tank body under various filling ratios under two working conditions: sudden braking and sharp turning of the tanker. The maximum stress and occurrence time of the wave-proof board and tank body are obtained, and the impact of liquid sloshing on the tank body and wave-proof board is obtained.

2. Construction of simulation analysis model

2.1 Tank structure modeling

The structure of the tank body of the liquid tanker is shown in Figure 1. The tank body consists of three parts: front and rear heads, wave-proof boards, and a cylinder. There are a total of three wave-proof boards, each of which is equipped with through-holes. The thicknesses of the cylinder and the wave-proof boards are 8mm and 6mm respectively. The tank body is made of aluminum alloy; the total length of the tank body is 6000mm. Referring to the actual structural two-dimensional CAD drawing dimensions of the tank body, a tank body model was established using SolidWorks, and the tank body was simplified without affecting its mechanical properties.

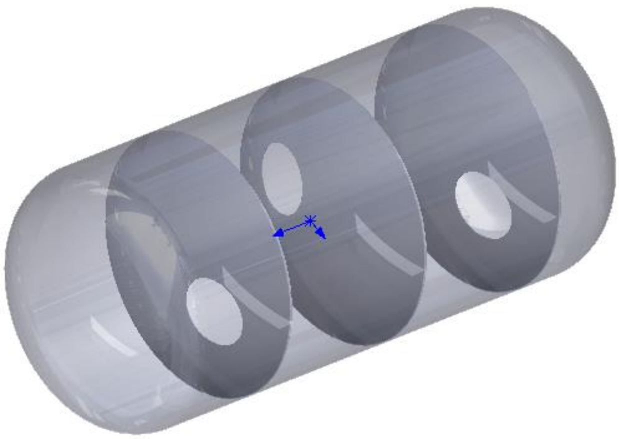


Figure 1 The tank model

When establishing the tank model, the forward direction of the tanker is defined as the positive direction of the X-axis of the tank model, and the vertical direction (Z-axis) of the tank model is consistent with the Z-axis of the vehicle coordinate system. For specific structural dimensions of the tank, refer to Figure 2.

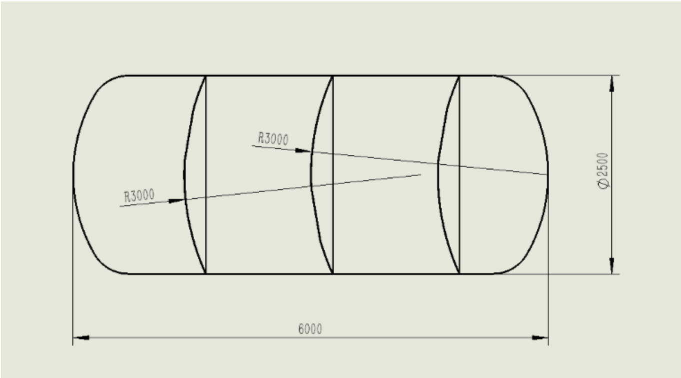


Figure 2 Structural dimensions of the tank body

The materials used in the simulation analysis of the paper are fluid materials and tank materials. According to "GB 18564.1-2019 - Road Transport of Dangerous Goods in Liquid Form - Tank Vehicles - Part 1: Technical Requirements for Metal Atmospheric Pressure Tanks"[6], water is used as the base medium for tank testing. The fluid domain contains two media: liquid water and air. The density of liquid water is 1000 Kg/m^3, and its viscosity is 0.001 mm^2/s. In ANSYS-Fluent calculations, water is selected as the base medium for fluid calculations, and water is used as the fluid material when setting up the fluid domain. The tank and wave-proof plate are made of aluminum alloy, and their material property parameters are shown in Table 1.

Table 1 Material characteristic parameters

Material Name	Mass density (kg/m^3)	Poisson's ratio	Elastic modulus (MPa)	Yield strength (MPa)
7075 aluminum alloy	2700	0.3	7.20E+04	455

2.2 Establishment of finite element model for tank structure

Using SpaceClaim, the tank model is divided into a fluid domain and a structural domain model. The internal volume of the fluid domain model is large, and due to gaps between the wave-proof boards, excessive mesh quantity and errors in mesh generation can lead to simulation result errors. Meshing exhibits good stability during grid generation. In finite element mesh calculations, a tetrahedral mesh is used for the fluid domain, with smooth transitions between meshes[7]. The fluid domain and structural domain models are shown in Figures 3 and 4; the fluid domain has 1,063,381 meshes and 191,127 nodes; the structural domain has 47,581 meshes and 94,101 nodes.

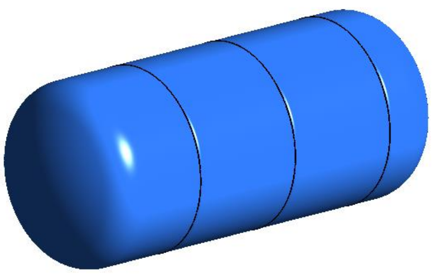


Figure 3 Tank fluid domain model

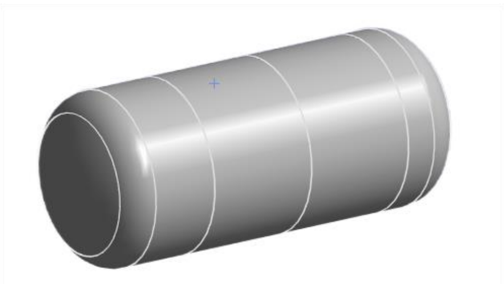


Figure 4 Container body domain model

2.3 Build a fluid-structure interaction simulation platform

To achieve bidirectional data exchange and collaborative computation in bidirectional fluid-structure coupling, it is necessary to interconnect the Fluent module, Transient Structural module, System Coupling module, and Results module. The Transient Structural module and Fluent module solve the structural and fluid domain models of the tank, respectively. The connection relationships between the modules are shown in Figure 5.

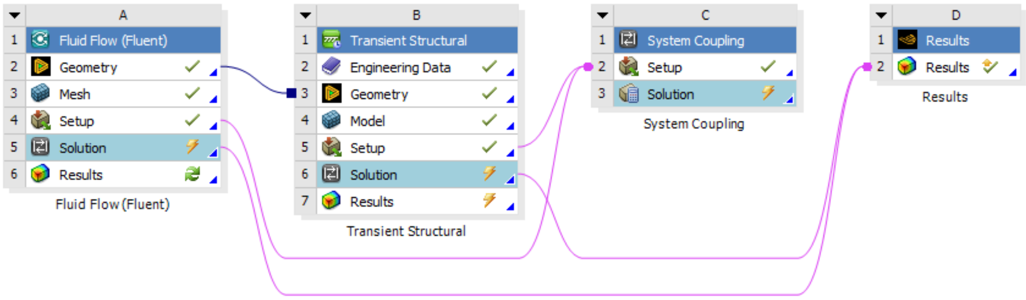


Figure 5 Bidirectional coupling analyzes the connection of each module

In each computational time step of bidirectional fluid-structure coupling, System Coupling transfers the pressure generated by fluid sloshing to the structure, and then transfers the displacement generated by the structure to the fluid, forming a closed-loop system of mutual influence. If the time steps of various modules in bidirectional fluid-structure coupling are not consistent, it may lead to data transfer delays. Therefore, the computational time steps of each module should be set to be the same. The computational time steps for the fluid module, transient structure module, and System Coupling are set to 0.01s, with a total of 200 calculations, and the simulation duration is set to 2s.

2.4 Bidirectional fluid-structure interaction analysis setup

The liquid sloshing in the tank varies with time, thus a transient solution is adopted. The VOF method is used to describe the free liquid surface. In the VOF gas-liquid two-phase flow setting process, it is necessary to define the primary phase and the secondary phase. The primary phase is water, and the secondary phase is air. Since the main consideration is the impact of liquid sloshing on the tank during transportation, both the inlet and outlet are kept closed, and the tank is considered as a closed whole. All defined boundary conditions are set to "wall". The pressure-velocity coupling solution method is selected as PISO, with the pressure relaxation factor set to 0.3, and all other relaxation factor parameters are set to 1.

2.5 Boundary conditions

When a tanker truck brakes suddenly on a dry asphalt road, it can achieve a maximum deceleration of 0.8g. Under sudden braking conditions, the tank body applies a deceleration of 8m/s^2 along the X-axis direction, and applies a gravitational acceleration in the negative direction of the Z-axis; under sudden turning conditions, the tank body applies a maximum deceleration of 8.0m/s^2 along the X-axis direction, and applies a maximum lateral acceleration of 4.0m/s^2 along the Y-axis direction, also applying a gravitational acceleration in the negative direction of the Z-axis.

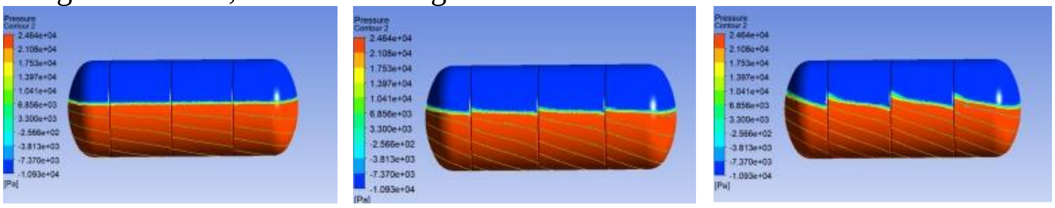
2.6 Stress evaluation

Since the tank body is made of 7075 aluminum alloy, with a yield strength of 455MPa, the tank body is analyzed and designed using the stress classification method according to GB 150-2011 "Pressure Vessels"[8] and JB4732-1995 "Steel Pressure Vessels - Analysis and Design Criteria"[9]. The safety factor is 1.5, and the calculated allowable stress of the tank body is 303MPa.

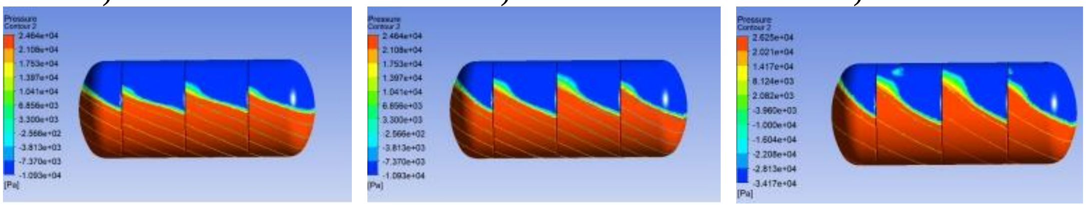
3. Stress analysis of the tank body under conditions of sudden braking and sharp turning

3.1 Sudden braking condition under 60% filling ratio

When the tanker is under sudden braking conditions, the distribution of gas-liquid two-phase in the tank changes over time, as shown in Figure 6.



a) initial moment b) After 0.4s c) After 0.8s



d) After 1.2s e) After 1.6s f) After 2.0s

Figure 6 Gas-liquid two-phase distribution diagram in the tank under emergency braking conditions with a 60% filling ratio

As shown in Figure 6, the fluid surface is horizontal at the initial moment. With the application of load and the passage of time, the water, represented by the red part, tilts forward, while the air, represented by the blue part, tilts backward. The liquid surface at the forefront tilts the highest, and the inclination of the liquid surface increases with time. As time goes by, the volume of liquid in the front chamber gradually increases, while the volume of liquid in the rear chamber gradually decreases.

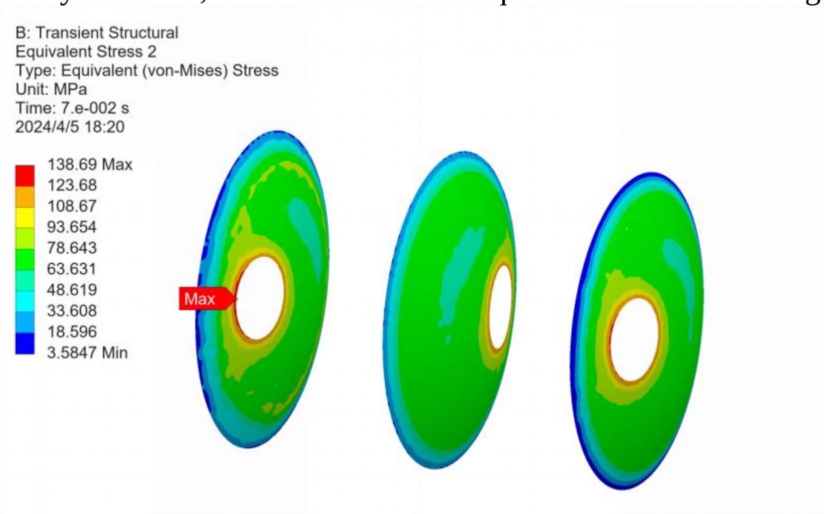


Figure 7 Stress contour plot of the wave-proof plate under emergency braking conditions with a 60% filling ratio

From Figure 7, it can be seen that when the tanker brakes suddenly, the stress generated by the sloshing liquid on the wave-proof plate is mainly concentrated at the circumference of the through-hole of the wave-proof plate. The maximum stress occurs at 7.e-002s, with a maximum stress value of 138.69 MPa. The maximum stress is located around the through-hole of the front wave-proof plate of the tank body.

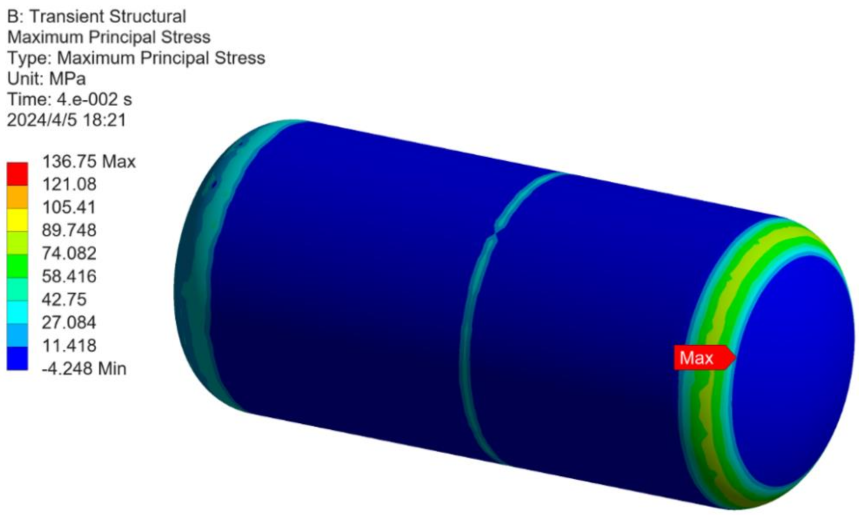
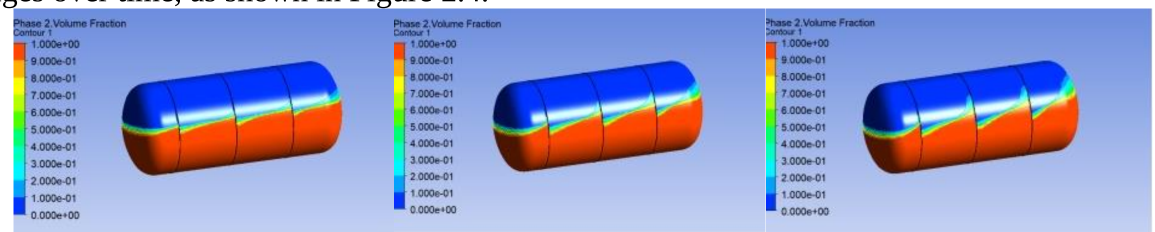


Figure 8 Maximum stress nephogram of the tank body during sudden braking with a 60% filling ratio

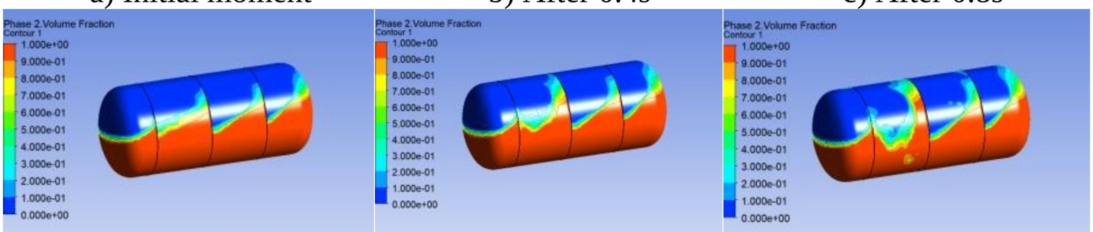
The maximum stress of the tank body under emergency braking conditions is shown in Figure 8. During emergency braking, the maximum stress experienced by the tank body is 136.75 MPa, occurring at 4.e-002s. The maximum stress is located at the junction between the front head and the cylinder.

3.2 Sharp turn condition under 60% filling ratio

When the tanker is in a sharp turn condition, the gas-liquid two-phase distribution in the tank changes over time, as shown in Figure 2.4.



a) Initial moment b) After 0.4s c) After 0.8s



d) After 1.2s e) After 1.6s f) After 2.0s

Figure 9 Gas-liquid two-phase distribution diagram in the tank under sharp turning conditions with a 60% filling ratio

As shown in Figure 9, during motion, the liquid initially impacts the tank body as a whole to the right, reaching the peak of sloshing in the foremost chamber at the second second; due to the presence of a wave-proof plate inside the tank, the amplitude of forward and backward sloshing during sharp turns is significantly suppressed.

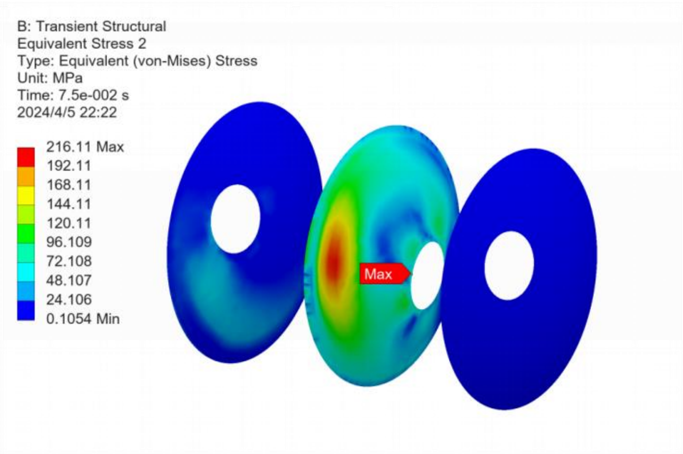


Figure 10 Maximum stress contour plot of the wave-proof plate under 60% liquid filling and sharp turning conditions

As shown in Figure 10, under the condition of sharp turning, the maximum stress of the wave-proof board is 216.11 MPa, occurring at the moment of 7.5e-002s, and its location is on the left side of the middle wave-proof board. Compared with the condition of sudden braking, the stress is greater. Under the condition of sharp turning, the tank body bears the composite acceleration in the direction of travel and lateral direction. The multi-directional inertial forces generated by this jointly act, significantly intensifying the sloshing intensity of the liquid inside the tank.

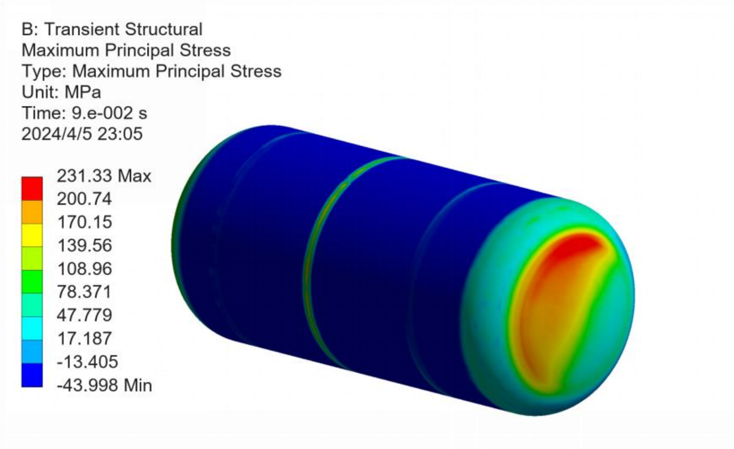


Figure 11 Maximum stress contour plot of the tank body under sharp turning conditions with a 60% filling ratio

The maximum stress nephogram of the tank body is shown in Figure 11. The maximum stress of the tank body is 231.33 MPa, occurring at 9.e-002s during the sharp turn of the tank body. Compared to the sudden braking condition, the time of maximum stress occurrence is delayed, and the maximum stress of the tank body is located at the junction of the rear head and the cylinder.

3.3 Stress analysis of tank bodies under different filling ratios

3.3.1 Stress analysis of the tank body under different filling ratios under emergency braking conditions

To investigate the impact of different filling ratios on the stress of the tank body and wave-proof board under sudden braking conditions, this paper sets three filling ratios of 60%, 70%, and 80% to simulate sudden braking conditions. The maximum stress variation curves of the tank body and wave-proof board are shown in Figures 12 and 13, respectively.

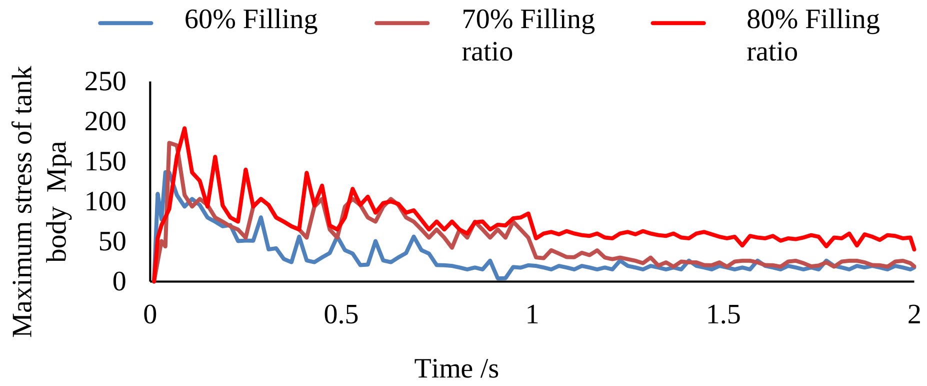


Figure 12 Time history of maximum stress in the tank body under emergency braking conditions

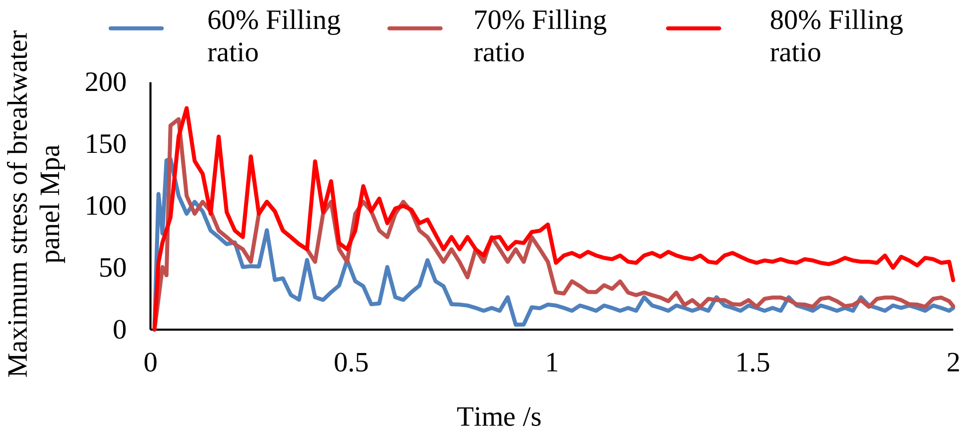


Figure 13 Time history of maximum stress of the wave-proof plate under emergency braking conditions

As can be seen from Figures 12 and 13, the tank body and the wave-proof board experience the maximum stress during the sudden braking of the tanker within 0 to 0.5 seconds. As the filling ratio increases, the stress on the tank body and the wave-proof board gradually increases with time, and the rate of stress growth accelerates. The maximum stress on the tank body and the wave-proof board occurs at 0.05 to 0.20 seconds when the filling ratio is 80%, reaching 191.43 MPa and 179.46 MPa respectively. As time continues to progress, the stress amplitude gradually decreases.

3.3.2 Stress analysis of tank body under different filling ratios under sharp turning conditions

The time history of the maximum stress on the tank body and wave-proof plate under sharp turning conditions is shown in Figures 14 and 15.

From Figures 14 and 15, it can be seen that under the condition of sharp turning, the tank body and the wave-proof board experience the maximum stress with a filling ratio of 80%, which are 270.12 MPa and 261.76 MPa respectively. This maximum stress occurs between 0.05 and 0.10 seconds, and the stress amplitude gradually decreases with time. This is within the allowable limit stress of 303 MPa for the tank body.

The maximum stress in the tank body occurs under the condition of a sharp turn with a filling ratio of 80%. The maximum stresses on the tank body and the wave-proof plate are 270.12 MPa and 261.76

MPa respectively. Both the maximum stresses are less than the allowable limit stress of 303 MPa, indicating that both the tank body and the wave-proof plate meet the strength requirements.

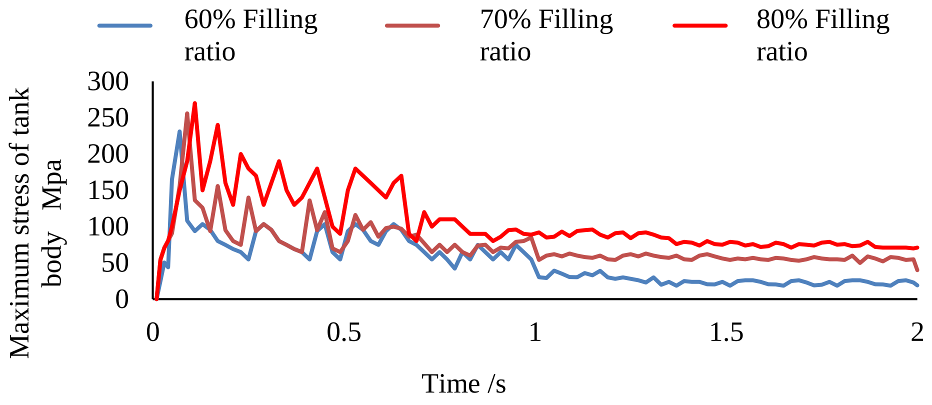


Figure 14 Time history of maximum stress in the tank body under sharp turning conditions

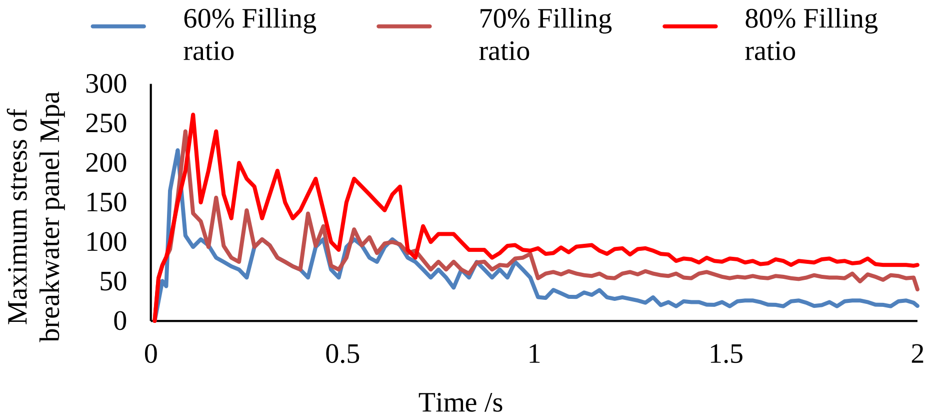


Figure 15 Time history of maximum stress on the wave-proof board under sharp turning conditions

4. Conclusion

This paper utilizes the finite element simulation analysis software ANSYS and employs a bidirectional fluid-structure coupling method to analyze the impact of three different filling ratios on the sloshing of liquid inside the tank during sudden braking and sharp turns of the tanker, revealing the sloshing patterns:

(1) When the filling ratio is 60%, under sudden braking conditions, the maximum stress caused by liquid sloshing on the front and rear heads, cylinder, and wave-proof plate occurs at the circumference of the through-hole of the wave-proof plate; under sudden turning conditions, the maximum stress in the tank body is located at the junction of the rear head and the cylinder.

(2) Under emergency braking and sharp turning conditions, the greater the filling ratio, the greater the impact stress on the tank body and the wave-proof plate, and the filling ratio is directly proportional to the stress. Under emergency braking conditions, when the filling ratio is 80%, the tank body and the wave-proof plate experience the maximum stress, which are 191.43 MPa and 179.46 MPa respectively. Under sharp turning conditions, when the filling ratio is 80%, the tank body and the wave-proof plate experience the maximum stress, which are 270.12 MPa and 261.76 MPa respectively. Both the maximum stress of the tank body and the wave-proof plate are less than the allowable limit stress of 303 MPa, meeting the strength requirements.

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