World Journal of Engineering Research
Print ISSN: 2959-9865
Online ISSN: 2959-9873
DOI: https://doi.org/10.61784/wjer3053

THE INFLUENCE OF HINGE ANGLE ON LIQUID SLOSHING IN ARTICULATED LIQUID TANKER

YuHang Mao
Huaiyin Institute of Technology, Huaian 223200, Jiangsu, China.
Corresponding Email: 2640809971@qq.com

Abstract: In the process of road driving, there are many reasons for the rollover of the tank truck, but due to the influence of liquid sloshing in the tank, the probability of rollover of the tank truck when turning will be greatly increased. In order to more clearly understand the influence of liquid sloshing in the tank and the factors affecting liquid sloshing, different hinge angles are used to analyze the liquid sloshing of the tank truck. Through the change of lateral torque and lateral acceleration of liquid sloshing in the tank, the influence of hinge angle on liquid sloshing and lateral acceleration is reflected. Then, the orthogonal experiment is used to verify the influence of hinge angle, filling rate and filling medium on liquid sloshing. Finally, it is confirmed that hinge angle and other factors have influence on liquid sloshing.
Keywords: Splice angle; Liquid sloshing; Orthogonal experiment

1 INTRODUCTION

Under the influence of the external environment, the sloshing of the liquid in the tank not only causes damage to the tank, but also has a certain impact on the driving of the liquid tanker. Therefore, it is of great significance to study the sloshing of the liquid in the tank to ensure the safety of the liquid tanker[1].

In order to determine the influence of bilateral curved baffles on the sloshing effect of spherical tanks, Al Yacouby Ahmad Mahamad et al. used ANSYS CFX software for numerical simulation, and used 0.55 and 0.8 liquid tanks to test the influence of baffles according to different filling rates of liquid tanks[2]. According to the factors such as the liquid sloshing force and the sloshing moment peak of the baffle, the conclusion is that the sloshing force, sloshing velocity and sloshing moment of the liquid sloshing in the liquid tank can be reduced by adding a suitable wave-proof baffle.

Zhang Xingying used the computational fluid dynamics method to numerically simulate the longitudinal liquid impact behavior of partially filled tanks[3]. By systematically investigating the key parameters such as filling ratio, tank geometry, longitudinal acceleration excitation characteristics and anti-sloshing device configuration, the influence of the above factors on the liquid impact load on the tank wall was quantitatively analyzed. Combined with the analysis of fluid dynamic characteristics, the steady-state amplitude, characteristic frequency and system damping of the maximum impact pressure in the tank under different working conditions are obtained, which provides a theoretical basis for the structural safety design and stability control of the liquid tanker. According to the fluid dynamics, the functions of the anti-wave plate setting and tank shape of the equivalent mechanical model are derived.

Liu et al. aimed at the transportation safety problem caused by the liquid sloshing in the tank[4]. Based on the model of a single anti-wave plate, Fluent fluid simulation was carried out on the liquid sloshing in the tank during the braking process. The two-way coupling method was used to study the distribution of gas and liquid in the tank during the braking process. According to the liquid dynamics and Euler multiphase flow model, the results show that the maximum shear stress of the anti-wave plate decreases nonlinearly with the increase of shear modulus.

Qi Ruiyun proposed a novel constrained attitude tracking control and active sloshing suppression scheme, which suppresses liquid sloshing by limiting the amplitude of angular velocity, control torque and its change rate[5]. The neural network method is used to obtain the sloshing force and sloshing torque caused by liquid sloshing, and a nonlinear disturbance observer is designed to deal with external disturbances.

Korkmaz Fatih Cuneyd studied the effect of stratified liquid on tank sloshing[6]. Five different fluids were used to explore the relationship between viscosity and free surface deformation and fluid impact on the side wall. A variety of fluid and high-speed imaging techniques were used to track the free surface deformation in single-layer and double-layer tests. The experimental results show that the lower fluid has experienced a significant damping effect.

Zheng et al. explored the role of the anti-wave plate in the non-full-load tank truck, and used the finite volume method to numerically simulate the tank truck under braking conditions[7]. The effects of the same filling rate, external excitation, pressure on the anti-wave plate, and the oscillation response of the gas-liquid interface were analyzed. The experiment shows that the anti-wave plate reduces the influence of liquid sloshing in the tank and reduces the gas-liquid interface fluctuation during the violent sloshing of the liquid.

In order to study the influence of the anti-wave plate on the liquid hydrogen tank, Jiang Rui et al. established a non-isothermal two-dimensional numerical model of the vehicle-mounted liquid hydrogen tank, and carried out thermodynamic simulation experiments[8]. The wave baffle reduced the sloshing amplitude of the liquid in the inner cylinder chamber. In addition, the wave baffle also played a ' thermal bridge ' role to a certain extent, forming a certain high temperature zone. Wang et al. studied the coupling effect of different media in the process of sloshing, analyzed the pressure of the whole tank structure and all wave-proof plates, and the gas-liquid two-phase distribution characteristics of liquid sloshing in the tank[9]. The results show that the change of filling medium will not change the gas-liquid two-phase distribution characteristics of liquid sloshing in the tank, but will change the pressure on the surface of the wave-proof plate. Quansheng Zang proposed a new method to study the nonlinear liquid sloshing in the tank: isogeometric boundary element method (IGBEM), which can be used to study the discrete control of nonlinear liquid sloshing in the tank[10]. By creating a fixed coordinate system and a local rectangular coordinate system that can move synchronously in the center of mass of the tank and combining with the semi-Lagrangian function method, the non-uniform B-spline (NURBS) is used as the property function. The designed geometric boundary is used to describe the trajectory of liquid sloshing. The nonlinear discrete equation of liquid sloshing in the tank is successfully obtained by the designed method.

2 FLUENT SIMULATION

2.1 Parameter Design

In order to verify whether the hinge angle has an effect on liquid sloshing, the size of the hinge angle is fixed to ensure that the size of the hinge angle remains unchanged in the experiment and other factors will not change. After that, the fluid simulation experiment is carried out after being divided into 6 groups as shown in Table 1. The peak value of the lateral impact force and the peak value of the lateral acceleration of the liquid are used to preliminarily determine whether the hinge angle has an effect on the liquid sloshing in the tank.

Table 1 Hinge Angle Size

Hinge angle size(°)	5°	10°	15°	20°	25°	30°
Filled Gas	Preppie	Preppie	Preppie	Preppie	Preppie	Preppie
Filling Ratio	70%	70%	70%	70%	70%	70%

2.2 Experimental Design

The tank body of the liquid tank truck designed in this paper is 10 m long, the long axis is 2.3 m long, and the short axis is 1.87 m long. The established Solidworks model diagram is imported into ANASY FLUENT, and the model is simplified. After that, the whole vehicle is designed and meshed. The tetrahedral mesh is selected as the meshing form, and the mesh size is selected as : 80mm, to ensure that the overall mesh quality is greater than 0.2, so as to ensure that the mesh will not break during the simulation. Then, the step size design and speed setting are carried out to ensure that the tank truck can reach the same speed at the same time. The final basin volume is shown in Figure 1.

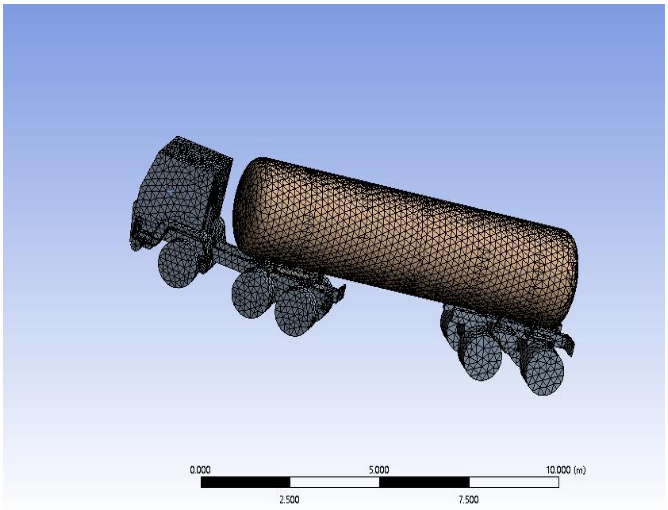

Figure 1 30 ° Hinged Angle Liquid Tanker Model Diagram

The components in the tank are mainly stupid and air, so it is treated as a two-phase flow problem. The turbulence model in the VOF model is selected for setting, and the implicit volume force is used for local balance. Then, in order to make the liquid sloshing more real, the dynamic mesh division is adopted, and the diffusion form is selected. After the setting is completed, the iterative step size and control accuracy are designed in WORKBENCH to ensure the accuracy of the experiment.

2.3 Result Analysis

Through six groups of experiments, the relationship between the lateral impact force and the lateral acceleration of each group with time is obtained, as shown in Figure 2 and Figure 3, because the six groups of experiments are from 0 to the same acceleration at the same time to achieve the same speed, the data is not much different, Figure 3 is the local amplification diagram of Figure 2. It can be seen from Figure 2 that with the increase of the hinge angle, the lateral impact force of the liquid increases, the increase speed of the lateral impact force also increases, and the peak value of the lateral impact force also increases. After reaching the first peak in 0.53 seconds, the increase rate of lateral impact force begins to increase, and then reaches the second peak, and the nonlinearity of liquid sloshing also increases. With the increase of the hinge angle, the arrival of the liquid impact force is gradually accelerated, as shown in Table 2.

Table 2 Peak Value and Time of Lateral Impact Force

Hinge angle size(°)	5°	10°	15°	20°	25°	30°
peak value of impact force(N)	6084.791	6263.135	6486.309	6669.181	6726.842	6822.35
Time(S)	0.35	0.37	0.38	0.4	0.41	0.43

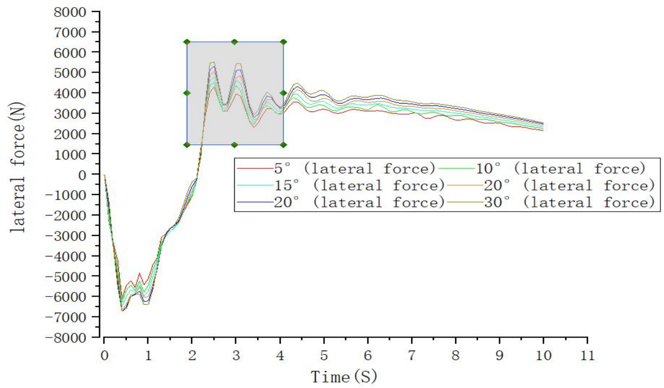

Figure 2 Liquid Sloshing Impact Force Diagram

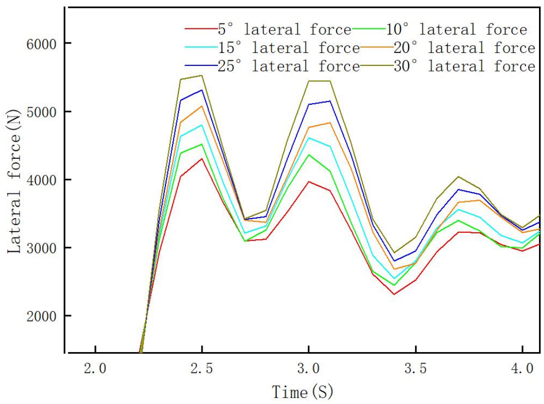

Figure 3 Local Enlargement

As shown in Figure 4, the relationship between the peak lateral acceleration and the hinge angle shows that as the hinge angle increases, the lateral acceleration also increases. For every 5 ° increase in the hinge angle, the peak lateral acceleration increases by approximately 0.2, which is approximately linear.

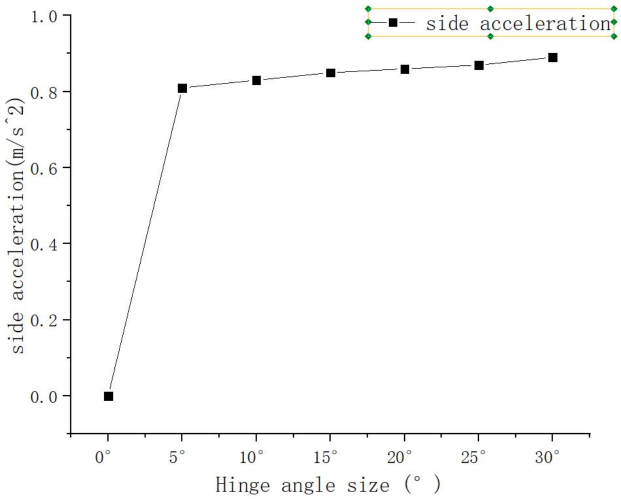

Figure 4 Relationship between Peak Lateral Acceleration and Hinge Angle

3 HINGE ANGLE ON THE LIQUID SLOSHING VERIFICATION

SPSSAU (Statistical Product and Service Software Automatically) is a powerful online data analysis platform. It provides efficient and convenient data analysis solutions through intelligent operation interface and rich analysis functions. The operation mechanism is concise, and the interaction mode of ' drag and drop ' is adopted. Only by uploading data, selecting variables and methods, the standardized results and charts can be generated at one click. The function is comprehensive and powerful. It provides 13 modules, covering about 500 algorithms, from basic descriptive statistics, T test, variance analysis, to advanced structural equation model, machine learning, Meta analysis, etc., to meet the needs of many fields.It not only inherits the statistical rigor of traditional professional software (such as SPSS), but also greatly improves the efficiency and accessibility of data analysis through automation, intelligence and cloud-based innovation.

3.1 Orthogonal Experiment

With the preliminary verification, the liquid sloshing will increase with the increase of the hinge angle, but the lateral acceleration will also affect the liquid sloshing in the tank, and the liquid lateral impact force may be affected by other factors. Therefore, further research is needed to see whether the hinge angle affects the liquid sloshing in the tank, which is indirectly affected by the lateral acceleration or directly affected by the hinge angle. In this paper, the orthogonal experiment method is used to verify the influence of liquid sloshing with other factors. Li proved that lateral acceleration, filling medium and filling rate have an effect on liquid sloshing[11]. Because it has been proved that the hinge angle has an effect on the lateral acceleration, and the orthogonal experiment needs no effect between the various factors, only the three factors of hinge angle, filling medium and filling rate are selected to verify the effect on liquid sloshing through experiments. The orthogonal table design was carried out by SQUSSA software, and the orthogonal test table of L (43) was selected. Four factors were selected for each factor, and 16 groups of experiments were formed by permutation and combination to verify the results.

3.1.1 Selection of hinge angle

According to the national regulations, the size of the hinge angle is generally not greater than 30 °, and the actual size of the hinge angle is generally greater than 5 ° during the turning process of the tanker. According to the results of the above 6 groups of experiments, the selected hinge angles are 10 °, 15 °, 20 ° and 25 °.

3.1.2 Selection of filling rate

According to the provisions of GB [12], the liquid tanker must retain 7 % -8 % of the air space and the maximum filling mass per unit volume allowed by the medium density at this temperature during transportation. And according to the understanding of the actual transportation situation, the filling rate should be selected 50 %, 70 %, 80 % and 90 %.

3.1.3 Selection of filling medium

In order to ensure the accuracy and universality of the experiment, the choice of filling medium should be related to viscosity and density. The selected filling medium is shown in Table 3.

Table 3 Filling Medium Selection Table

Filled Gas	Diesel Oil	Preppie	Liquefied LNG	Crude Oil
Viscosity kg/m^3	0.0025	0.000589	0.00016	0.5
Density $[kg/(m*s)]$	850	875	450	960.9

3.2 Range Experiment

Through the designed orthogonal table, the above FLUENT simulation experiment is carried out, and 16 groups of experiments are organized into the required orthogonal table, as shown in Table 4. The sorted orthogonal table was imported into SPSSAU for range experiment, and the results were obtained according to the following equation.
The i-th level for factor A:

$$\bar{K_{Ai}} = \frac{1}{m}\sum_{k=1}^{m} y_{ai}, k \tag{1}$$

Range calculation:

$$R_A = max\left(\bar{K_{A1}}, K_{A2}, \bar{K_{A3}}, \bar{K_{A4}}\right) - min\left(K_{A1}, K_{A2}, \bar{K_{A3}}, \bar{K_{A4}}\right) \tag{2}$$

Table 4 Orthogonal Experimental Table

Test Times	A	B	C	D	Index
1	50%	Diesel Oil	10°		2630.166
2	70%	Crude Oil	15°		4338.972
3	80%	Preppie	20°		6669.191
4	90%	Liquefied LNG	25°		2165.96
5	50%	Diesel Oil	15°		6304.223
6	70%	Crude Oil	20°		8121.474
7	80%	Preppie	25°		6263.135
8	90%	Liquefied LNG	10°		2246.575
9	50%	Diesel Oil	20°		8322.563
10	70%	Crude Oil	25°		8376.799
11	80%	Preppie	10°		5999.459
12	90%	Liquefied LNG	15°		3806.965
13	50%	Diesel Oil	25°		8805.877
14	70%	Crude Oil	10°		6916.421
15	80%	Preppie	15°		8525.87
16	90%	Liquefied LNG	20°		6617.991

As shown in Table 5 of the range analysis and Figure 5 of the horizontal factors, the best combination of the three factors is : the filling rate is 50 %, the hinge angle is 10 °, and the lateral force of this combination is the smallest. The filling rate has the greatest influence on the liquid sloshing, followed by the filling medium, and the hinge angle has the least influence.

Table 5 Range Analysis Table

item	level	A	B	C
K value	1	15804.29	27753.67	17792.62
	2	22935.41	26062.83	22976.03
	3	26505.79	14837.49	29731.22
	4	30866.16	27457.65	25611.77
K avg value	1	3951.07	6938.42	4448.16
	2	5733.85	6515.71	5744.01
	3	6626.45	3709.37	7432.81
	4	7716.54	6864.41	6402.94
best level		1	3	1
R		-3765.47	-3229.04	-2984.65
Number of levels		4	4	4
Repeats per level R		4.0	4.0	4.0

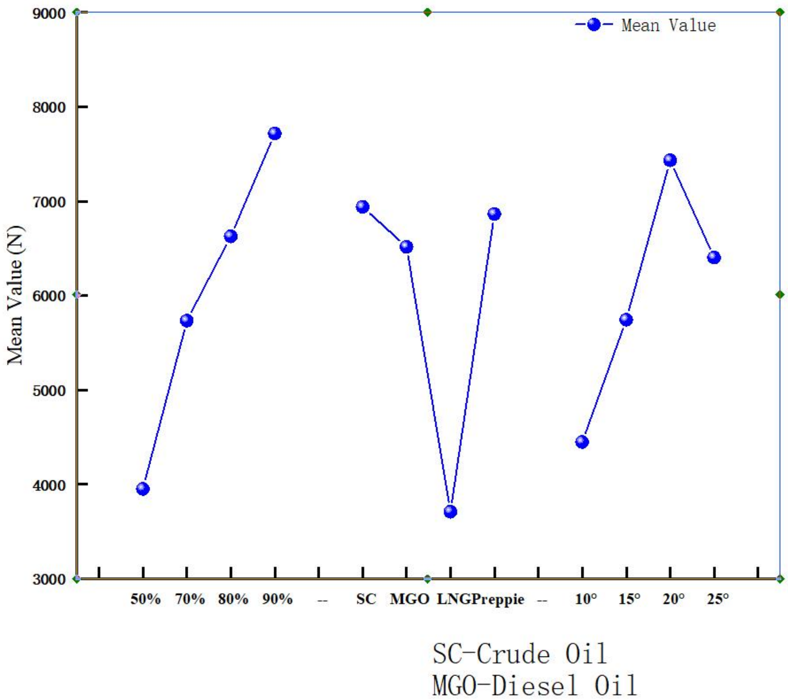

Figure 5 Analysis Chart of Each Factor Level

3.3 Variance Experiment

After the range experiment, it is determined that the three factors will affect the liquid sloshing in the tank. Then the orthogonal diagram is imported into the orthogonal experiment module of SPSSAU, and the experiment is calculated by the following formula. Strict significance test and quantitative analysis are carried out to obtain reliable conclusions.

Total sum of square:

$$SS\_T=\sum\sum y_{ij}^2-\frac{\sum\sum y_{ij}^2}{N} \tag{3}$$

Inter-group sum of squares:

$$SS\_A=\frac{\sum(T_i^2/n_i)-T^2}{N} \tag{4}$$

Intra group variance:

$$SS_E=SS_T-SS_A \tag{5}$$

Total degree of freedom:

$$df_T=N-1 \tag{6}$$

Degree of freedom between groups:

$$df_A=k-1 \tag{7}$$

Intra-group freedom:

$$df_E = N - k \tag{8}$$

Mean square between groups:

$$\mathrm{MS\_A} = \frac{\mathrm{SS\_A}}{\mathrm{df\_}} \tag{9}$$

Mean square within group:

$$\mathrm{MS\_E} = \frac{\mathrm{SS\_E}}{\mathrm{df\_E}} \tag{10}$$

F Value:

$$\mathrm{F} = \frac{\mathrm{MS\_A}}{\mathrm{MS\_E}} \tag{11}$$

As shown in Table 6 of the analysis of variance, when the P value is less than 0.05, there is a 95 % probability that there is a relationship between the two. It can be seen that the three factors are significantly different from the liquid sloshing in the tank, indicating that the hinge angle has a significant effect on the liquid sloshing, providing strong evidence for subsequent research.

Table 6 Variance Analysis Table

	quadratic sum	df	mean square	F	p
intercept	577340531.052	1	577340531.052	2176.622	0.000
A	30430762.198	3	10143587.399	38.242	0.000263
B	28562281.404	3	9520760.468	35.894	0.000315
C	18755421.674	3	6251807.225	23.570	0.001016
residual error	1591476.743	6	265246.124		

4 CONCLUSION

According to the simulation results of FLUENT and SPSSUA, it can be seen that the size of the hinge angle has a significant effect on the liquid sloshing, not the indirect effect of lateral acceleration.

(1) The hinged angle has an effect on the lateral acceleration. As the hinged angle increases, the lateral acceleration also increases. However, it cannot be proved whether the hinged angle directly affects the liquid sloshing, or whether the hinged angle directly affects the lateral acceleration and indirectly affects the liquid sloshing.

(2)The lateral acceleration increases with the increase of the hinge angle, and the increase trend of the lateral acceleration is approximately linear. For every 5°increase in the hinge angle, the approximate increase is 0.2.

(3)The filling rate, filling medium and hinge angle have an impact on the liquid sloshing in the tank. Among them, the filling rate has the greatest impact, followed by the filling medium, and the hinge angle has the least impact. However, the $P < 0.5$ of the hinge angle can prove that the hinge angle has a direct impact on the liquid sloshing, and is not indirectly caused by the lateral acceleration.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

REFERENCE

[1] Cao Y, Ma L, Gu Y, et al. Effect of braking impact of hazardous chemicals tanker on tank. Petrochemical equipment technology, 2025, 46(01): 7-14+75. DOI: CNKI: SUN: SHSJ.0.2025-01-003.

[2] Al-Yacouby A M, Ahmed M M, Liew M S. The Effects of Double-Side Curved Baffle Height on the Liquid Sloshing of a Spherical Tank—Numerical Study//Advances in Material Science and Engineering: Selected Articles from ICMMPE 2021. Singapore: Springer Nature Singapore, 2022, 55-69.

[3] Zhang Xingying. Research on the braking efficiency of tank car based on the analysis of the dynamic characteristics of longitudinal liquid impact. Jilin University, 2022. DOI: 10.27162/ d.cnki.gjlin.2022.003584.

[4] Liu X, Wang Xing, Xu Y. Two-way fluid-solid coupling numerical analysis of liquid sloshing in a moving tank. Journal of Xi 'an Jiaotong University, 2012, 46(05): 120-126. DOI: CNKI: 61-1069/ T.20120224.1036.007.

[5] Qi R, Dong X, Chao D, et al. Constrained attitude tracking control and active sloshing suppression for liquid-filled spacecraft. ISA transactions, 2023, 132, 292-308.

[6] Korkmaz F C. Damping of sloshing impact on bottom-layer fluid by adding a viscous top-layer fluid. Ocean Engineering, 2022, 254, 111357.

[7] Zheng Z, Zhang Z, Xu Y, et al. Study on the influence of wave-proof plate on the thermodynamics of non-fully loaded liquid hydrogen tank. Low temperature engineering, 2025(01): 94-100. DOI: CNKI: SUN: DWGC.0.2025-01-013.

[8] Jiang Y, Ding H, Hao C, et al. The effect of baffle on the dynamic and thermal characteristics of liquid hydrogen bottles under sloshing conditions. Low temperature and superconductivity, 2024, 52(10): 37-43+55. DOI: 10.16711/j.1001-7100.2024.10.006.

[9] Wang Jianye, Zhang Yin, Tang Zhenqi. Coupling analysis of impact sloshing of different liquid medium in tank of transport vehicle. Commercial vehicle, 2024(05): 78-81. DOI: 10.20042/ j.cnki.1009-4903.2024.05.004.

[10] Zang Q, Hong H, Liu J, et al. Isogeometric boundary element analysis of nonlinear liquid sloshing in containers under pitching oscillation. International Journal of Engineering Science, 2025, 217, 104371.

[11] Li Jie. Research on roll stability control of semi-trailer liquid tanker. Changchun University of Technology, 2018.

[12] Wang Lei. Research on anti-rollover stability of tank semi-trailer considering vehicle-liquid coupling. Harbin Institute of Technology, 2020. DOI: 10.27061/d.cnki.ghgdu.2020.00043.