Experimental Study on Liquid Sloshing of a Vane-type Surface Tension Tank for Satellite

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Received: 5 June 2022 / Accepted: 11 August 2022
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Abstract
This study conducts experimental research on the liquid sloshing performance of a vane-type tank used in high orbit satellites. The liquid sloshing tests of the tank without a propellant management device (PMD) were developed under different liquid-filling ratios. Liquid sloshing tests of the tank with PMD were performed in different directions and liquid-filling ratios. The experimental test results agree considerably with the theoretical results, indicating the test system’s reliability. A linear relationship was observed between the sloshing frequency and the liquid-filling ratio of the vertical installation test when the gas–liquid interface was in the hemisphere. The vertical installation test sloshing frequency remains unchanged when the gas–liquid interface is in the cylindrical section. The inverted conical accumulator structure of the PMD can increase the damping in the vertical installation tank. The sloshing mass in the vertical direction is less than that in the horizontal direction. Liquid sloshing results of the vane-type propellant tank will guide the design of spacecraft structures and control systems.

Keywords Vane-type tank · Liquid sloshing · Sloshing performance · Propellant management device · Experimental test

Introduction
A propellant tank is among the essential components of spacecraft. It is used to store and manage propellant and provide non-gas entrained propellant for engines or thrusters under the specified flow and acceleration conditions. The proportion of liquid fuel mass to a spacecraft’s total mass has increased with the continuous development of aerospace technology. Meanwhile, the requirements for the orbit and attitude control accuracy of the launch vehicle and spacecraft are increasing (Fries et al. 2012). The sloshing effects of liquid moving inside the propellant tank can significantly affect the guidance, navigation, and control (GNC) system performance due to the coupling between fuel and structure dynamics (Souza and Souza 2014). Therefore, the performance of tank liquid sloshing must be considered in designing spacecraft structures and control systems (Chiba and Magata 2017).

Theoretical analysis, numerical calculation, and experiment tests are typically used to study and analyze a tank’s liquid sloshing characteristics and related parameters (Zheng et al. 2021; Schröck et al. 2022). The launch vehicle and satellite’s attitude and orbit control system can be optimized according to the sloshing result (Fries et al. 2012). The interaction between the fluid and the tank walls can lead to instability problems and even mission failure. The combined liquid–structure dynamic coupling is usually extremely difficult to model for a space system (Angeletti et al. 2020).

The characteristic sloshing parameters can be obtained directly using experimental tests (Chintalapati et al. 2012, Y. Li et al. 2019).
The fluids sloshing behavior within a spherical tank under microgravity conditions was investigated through the FLUIDICS experiment conducted at the International Space Station (ISS) (Dalmon et al. 2019). The control of fluids in microgravity with vibrations experiment was performed to observe the potentially complex behavior of vibrated liquids in weightless environments (Fernandez et al. 2017). Hu et al. (2016) investigated the liquid sloshing of a net-type surface tension tank experimentally and concluded that the middle partition of the tank could reduce liquid sloshing. Lapilli (2015) performed a liquid sloshing experiment at the ISS.

Li et al. (2020) investigated the dynamic sloshing behavior in a model tank using the volume of fluid method. It was concluded that the sloshing behavior could be considerably captured using the selected dynamic contact angle model. Chiba and Magata (2020) analyzed the influence of liquid sloshing on the pitching dynamics of flexible space structures with liquid on-board. Colagrossi and Lavagna (2021) developed a vibration suppression attitude control system for spacecraft, with flexible appendages and internal liquid sloshing, undergoing a generic nonprescribed three-dimensional motion subjected to environmental disturbances. The finite volume and Lattice Boltzmann methods were proposed to quickly evaluate liquid slosh behavior under different container designs (Yang et al. 2021). Veldman et al. (2007) described a combined theoretical and experimental approach to study the influence of sloshing liquid on spacecraft dynamics. There are few studies on liquid sloshing tests of large capacity prototype propellant satellite tank.

Most present experimental tests for liquid sloshing in propellant tanks were conducted using a small-scaled tank. The liquid sloshing performance in a small-scaled tank was inconsistent with large prototype tanks. The effect of the propellant management device (PMD) on the liquid sloshing was different, which generated a difference in the gas–liquid interface. Most present numerical calculations for liquid sloshing only investigated the change of the gas–liquid interface, although it is difficult to calculate the sloshing mass and force.

A large capacity propellant tank with vane-type PMD was used for the experiment. The tank’s liquid sloshing performance was studied using the resonance-free attenuation sloshing and forced sloshing test methods.

**Structure of the Test Tank**

The test tank comprised a shell and vane-type PMD. The volume of the tank is 880 L. The shell is composed of two hemispheres and a cylindrical section. The structure of the vane-type tank is shown in Fig. 1. Figure 2 shows the structure of the vane; a is 60 mm, b is 15 mm. The thickness of the vane was 1 mm. The structure of the accumulator is shown in Fig. 3.
The test simulation tank shell and the prototype PMD were used in the liquid sloshing test. The tank tested in the experiment was composed of a plexiglass inner shell and an aluminum alloy frame, as shown in Fig. 4. The inner diameter of the shell was the same as that of the prototype tank, which met the observation and shooting requirements of the test. It has sufficient strength and stiffness to ensure the normal progress of the test. The upper hemisphere, cylindrical section, and lower hemisphere of the test tank were welded with the vane-type PMD as a whole structure.

Figure 5 shows the installation diagram of the vane-type tank on the satellite. The satellite has four vane-type tanks and six gas tanks. Vane-type tanks are installed along the satellite’s z-axis, and the satellite’s z-axis is consistent with the longitudinal axis of the carrier. According to the installation form of the PMD in the tank, the included angle between a pair of vanes and the X-direction was 56.1°.

**Test System and Test Method**

The sloshing test system consists of an excitation, support, lifting system, test tank, liquid filling and discharge system, measurement system and other subsystems. The push–pull equipment adopts a mechanical eccentric part with a frequency of 0–5 Hz and a thrust of 10 kN. The transmission device connects the test piece with the push–pull equipment, including clutch and braking devices. The supporting device can be used for the installation, lifting, weighing and turnover of the test tank. A small water pump was used to fill and discharge the liquid in the tank. The filling liquid capacities for various filling ratios were calibrated using a load cell. A displacement measurement was performed using a laser displacement sensor. The Π-type sensor was used to measure the sloshing force and moment.

The test system is shown in Fig. 6. The test supporting device with a height of 4 m was set up and hung with four pull rods, connecting the load cell in the middle of the pull rod to measure the liquid-filling ratio of the tank. The length of the pull rod $L_0$ is 2.5 m. The rectangular structure (B = 1.8 m, W = 1.2 m) is a supporting beam arranged along the sloshing direction. The spacing of the rectangular structure can be adjusted. Π-Type sensors were installed in the middle of the beam and used to fix the test tank. When the test tank was installed vertically, the liquid sloshing direction was horizontal (X-direction), as shown in Fig. 5. When the tank is installed horizontally ($\theta = 0$), the horizontal sloshing of the liquid is in the X-direction and the longitudinal direction is in the Z-direction. The front cross beam of the rectangular structure was connected to the driving rod of the push–pull equipment to transmit the horizontal movement, and the clutch braking device was connected in series in the middle of the driving rod. The rear cross beam of the rectangular structure was connected to the laser displacement sensor to measure the horizontal movement of the test tank. Since the tank is an axially symmetrical structure, the sloshing results in the x and y-directions are consistent.
Figure 7 shows the installation and excitation application direction of the sloshing test.

Sloshing tests of the tank were performed at constant ground gravity (1g0). Liquid sloshing parameters of the tank required for the design of attitude and orbit control system during launch, satellite apogee orbit change, and position maintenance were obtained, including sloshing frequency, sloshing mass, and sloshing damping under various working conditions. The above data were transformed into an equivalent pendulum model, and the corresponding parameters obtained. The sloshing force and torque can be tested using Π-type sensors. The other parameters were fitted using a free attenuation and forced sloshing tests. The free attenuation test obtains the sloshing frequency, height of the sloshing mass, and sloshing damping value. The forced sloshing test can obtain the sloshing mass and total centroid height. The height of the sloshing mass is the distance from the center of the sloshing mass to the bottom of the tank.

Table 1 shows the experimental information for the sloshing test. The excitation and installation directions can be seen in Fig. 7.

During the forced sloshing test, the positioning displacement excitation was adopted. The displacement of the tank is 5 mm. The sloshing equipment was started, and the vibration frequency was adjusted with the liquid resonance frequency. After the movement was stabilized, the time history of the test tank’s sloshing displacement, force, and torque was recorded. More than 50 vibration cycles were recorded for each test. The amplitude, phase, and frequency of displacement, force and torque could be calculated according to the recorded time history data. The value of the frequency response function could be estimated; after changing the vibration frequency, the recording process was repeated until tests of all frequencies were completed. The test frequency covered 0.5–2 times the first-order sloshing frequency.

During the resonance attenuation sloshing test, the vibration frequency of the sloshing equipment was set up with the liquid resonance frequency. The rectangular structure was locked when the sloshing amplitude reached a constant value. The time history data of the sloshing force was recorded to calculate the sloshing damping coefficient and sloshing frequency. Each test was repeated 6 – 8 times.

The sloshing tests of the tank in X, Y, and Z directions were performed to simulate the launch conditions, satellite apogee ignition, and position maintenance. The appropriate test medium for the liquid sloshing test was selected according to the analysis of similarity criteria and similar conditions. The acceleration generated by the satellite remote ignition was about 0.06–0.12 m/s², and the acceleration under East–West and North–South maintenance conditions were about 0.0045–0.009 m/s².

Measuring the specific gravity of the test medium (ρ) and viscosity coefficient (ν) was required to reduce the measurement error caused by temperature change. The Galileo number of the test medium before each test should be calibrated. According to the requirements of similar criteria, a mixture of 60% glycerol and water was used as the test liquid.

A liquid sloshing test was performed under 14 working conditions of liquid-filling ratio. As shown in Table 2, tests with selected working conditions were conducted under the test tank’s vertical and horizontal installation states. The weights of the liquid in the tank under different liquid-filling ratios are shown in Table 2.

Test Results

Relationship Between Viscosity and Temperature of the Test Medium

Before the sloshing test, the temperature and kinematic viscosity of the 60% glycerol and water mixture were
measured. According to the measurement results, the relationship between the kinematic viscosity and temperature of the mixture can be obtained, as shown in Fig. 8. The linear fitting formula is shown as follows,

\[ \nu = 0.4768T + 21.96 \]  

(1)

where, \( \nu \) is the kinetic viscosity coefficient; \( T \) is the temperature.

**Table 1** Experimental information

| No | Experimental subject | Installation direction | Excitation direction | Test methods                                           | Number of experiments |
|----|-----------------------|------------------------|---------------------|-------------------------------------------------------|-----------------------|
| 1  | Tank without PMD      | vertical               | X                   | forced sloshing test                                  | 24                    |
|    |                       |                        |                     | forced sloshing test                                  | 104                   |
| 3  | horizontal            | X                      |                     | resonance attenuation sloshing test                   | 78                    |
|    |                       |                        |                     | forced sloshing test                                  | 32                    |
| 4  | Tank with PMD         | horizontal             | Z                   | resonance attenuation sloshing test                   | 24                    |
|    |                       |                        |                     | forced sloshing test                                  | 32                    |
| 5  |                       | horizontal             | X                   | resonance attenuation sloshing test                   | 24                    |
During the test, the coverage range of the liquid’s temperature is 8.9 °C–29.7 °C, and the corresponding liquid kinematic viscosity range is 9.09–18.7 mm²/s. The kinematic viscosity of the glycerol solution decreases with the increase of the liquid’s temperature, which conforms to the theoretical law.

### X Direction Sloshing on a Vertical Installation without PMD

The liquid sloshing in a tank can be calculated using an equivalent dynamic model.

Figure 9 shows the equivalent dynamic model. $m_0$ is the total mass of the liquid, and $h_0$ is the height for the center of static mass. $m_i$ is the sloshing mass. $L_i$ is the equivalent pendulum length, and $h_i$ is the height of pendulum point.

The displacement of the sloshing mass relative to the tank is $U_{ri}$. The motion equation is shown as follows:

\[ m_i \ddot{U}_{ri} + c_i \dot{U}_{ri} + m_i g \frac{L_i}{U_{ri}} = -m_i \ddot{U} \]  
(2)

where $c_i$ is the equivalent viscous damping coefficient, and $U$ is the sloshing displacement of the tank.

$\omega$ is the natural sloshing frequency, $\xi$ is the damping ratio. $\omega$ can be calculated using Eq. (3).

\[ \ddot{U}_{ri} + 2\xi \omega \dot{U}_{ri} + \omega^2 U_{ri} = -\ddot{U} \]  
(3)

The sloshing force ($F$) and sloshing torque ($M$) can be calculated from the following equations.

\[ F = m_i \ddot{U} + m_i \ddot{U}_{ri} \]  
(4)

\[ M = F h_i = m_i h_i (\ddot{U}_{ri} + \ddot{U}) \]  
(5)

During the sloshing test, the sloshing force ($F$) and the acceleration of the test system can be the $\Pi$-type sensor. Then, the sloshing mass can be obtained.

Sloshing tests of tank vertically installed without the PMD was conducted to verify the test system. The liquid filling ratios were 0.2, 0.45, and 0.77. Figure 10 shows the

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| No | Filling ratio | Propellant weight of fuel tank (kg) | Propellant weight of oxidant tank (kg) |
|----|---------------|-----------------------------------|--------------------------------------|
| 1. | 0.95          | 731.33                            | 1209.05                              |
| 2. | 0.90          | 692.84                            | 1145.42                              |
| 3. | 0.85          | 654.35                            | 1081.78                              |
| 4. | 0.77          | 592.77                            | 979.97                               |
| 5. | 0.75          | 577.36                            | 954.51                               |
| 6. | 0.70          | 538.87                            | 890.88                               |
| 7. | 0.65          | 500.39                            | 827.24                               |
| 8. | 0.60          | 461.90                            | 763.61                               |
| 9. | 0.45          | 346.42                            | 572.71                               |
| 10.| 0.30          | 230.95                            | 381.80                               |
| 11.| 0.25          | 192.46                            | 318.17                               |
| 12.| 0.20          | 153.96                            | 254.54                               |
| 13.| 0.15          | 115.47                            | 190.90                               |
| 14.| 0.10          | 76.98                             | 127.27                               |

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**Fig. 8** Relationship between the kinematic viscosity and temperature

**Fig. 9** Equivalent dynamic model
comparisons between the sloshing frequency of the experimental result ($\omega_e$) and the theoretical value ($\omega_t$). The Results of the fitted total mass ($m$), the weighed total mass ($m_w$), the sloshing mass of the experiential result ($m_{ie}$), and the sloshing mass of the theoretical value ($m_{it}$) are shown in Fig. 11. The fitted total mass ($m$) can be calculated by Eq. (6). $m_w$ is the weighed total mass of the liquid during the sloshing process, including the liquid sloshing mass and static liquid mass. $m_{ie}$ is the sloshing mass weighed by the test system. $m_{it}$ is the sloshing mass calculated using the theoretical method.

$$m = m_i + m_0 + \sum_{i=1}^{n} m_i$$

(6)

The test results show that the maximum error of the sloshing frequency was 2.58% when the filling ratio was 0.77. The minimum error sloshing frequency was 0.53% when the filling ratio was 0.45. The maximum error of sloshing mass was 6.44% when the filling ratio was 0.77, and the minimum error of sloshing mass was 2.14% when the filling ratio was 0.45. The maximum error between the fitted total mass and the weighed total mass was 5.55% when the filling ratio was 0.2, and the minimum error was 0.99% when the filling ratio was 0.77. These system errors met the test requirements.

### X Direction Sloshing on a Vertical Installation with PMD

An X-direction sloshing test of the tank with PMD on vertical installation was performed. Figure 12 shows the relationship between the sloshing frequency and the liquid-filling ratio. The sloshing frequency increases approximately linearly from 0.1 to 0.3. The sloshing frequency increases slowly from 0.3 to 0.6, whereas it increases rapidly from 0.77 to 0.95. The liquid–gas interface with filling ratio from 0.1 to 0.3 is in the bottom hemisphere of the tank, so the frequency has a linear relationship with filling ratio. The liquid–gas interface with filling ratio from 0.3 to 0.77 is in the column section, so the frequency increases slowly due to the similar liquid level condition. The frequency is unchanged when the liquid–gas interface filling ratio was from 0.6 to 0.77. The liquid–gas interface with a filling ratio from 0.77 to 0.95 is in the upper hemisphere, so the frequency increases rapidly. There is a linear relationship between the sloshing frequency and the liquid-filling ratio when the liquid–gas interface was in the hemisphere. The sloshing frequency remains unchanged when the gas–liquid interface is in the cylindrical section. The shape evolution of gas–liquid interface in the cylinder remained the same with different filling ratios.

Figure 13 shows the curve of the damping with the liquid-filling ratio. The damping decreases rapidly with the liquid-filling ratio from 0.1 to 0.3 because the inverted conical accumulator structure of the PMD increases the damping in the tank. When the liquid-filling ratio is from 0.3 to 0.9, the damping is stable between 0.36%–0.43%. However, the damping increases slightly when the liquid-filling ratio is from 0.9 to 0.95. It can be seen that the effect of the accumulator on damping is still obvious when the liquid–gas interface is in the bottom hemisphere. At medium and high liquid-filling ratios, the influence of the four vanes of the PMD is not obvious. At a high liquid-filling ratio when the liquid–gas interface is in the upper hemisphere, the structure of the four vanes increases the resistance slightly, which is due to the four vanes being concave and tending to be more horizontal.
Figure 14 shows the height curves of the pendulum point and center of the sloshing mass with different filling ratios. The pendulum point height $h_i$ can be calculated during the resonance attenuation sloshing test.

$$h_i = \frac{1}{N} \sum_{k=1}^{N} \frac{M_k}{F_k}$$  \hfill (7)

$M_k$ is the $k$-th peak value of the torque curve, and $F_k$ is the $k$-th peak of the force curve.

The height of sloshing mass ($h_s$) can be calculated during the forced sloshing test.

$$h_s = h_i - L_i = \frac{1}{N} \sum_{k=1}^{N} \frac{M_k}{F_k} - \frac{g}{\omega^2}$$  \hfill (8)

The $h_i$ decreases slightly from 0.1 to 0.3, then rises continuously from 0.3 to 0.77, and rises slowly from 0.77 to 0.95. The $h_i$ increases approximately linearly from 0.1 to 0.95. The difference between the $h_i$ and the $h_s$ decreases first, then basically remains unchanged, and then decreases rapidly, which can correspond to the changing trend of frequency.

Figure 15 shows the curves of the sloshing mass, $m_s$ and $m_w$, with different liquid-filling ratios. The $m$ and the $m_w$ curves with the liquid-filling ratio have a good consistency. The relative error of all tested liquid-filling ratios is in the range of 1.41%–7.48%. The sloshing mass increases with an increase in the liquid-filling ratio from 0.1 to 0.3. From 0.3 to 0.85, the sloshing mass was basically unchanged, fluctuating slightly. From 0.85 to 0.95, the sloshing mass...
decreased significantly. The sloshing mass was highest when the liquid-filling ratio was 0.75.

Figure 16 shows the curve of the sloshing mass ratio ($m_s/m_w$) with the liquid-filling ratio. Generally, the proportion of the sloshing mass decreases with an increase in the liquid-filling ratio. The largest sloshing mass proportion, 70.14%, was observed when the liquid-filling ratio was 0.15.

**Z Direction Sloshing on a Horizontal Installation with PMD**

Horizontal sloshing of the tank occurs during attitude control after the satellite enters orbit. The residual fuel in the tank was almost less than 30% of the whole capacity; therefore, filling ratios, including 0.1, 0.15, 0.20, and 0.25, were chosen for the horizontal sloshing test.

The Z-direction sloshing results on the horizontal installation with PMD are shown in Figs. 17 and 18. The sloshing frequency increases approximately linearly with an increase in the liquid-filling ratio and the sloshing damping decreases with an increase in the liquid-filling ratio. The $h_i$ increases with the increase in the liquid-filling ratio and the $m_s$ has a linear relationship with the liquid-filling ratio. Liquid–gas interfaces of the four filling ratios were in the bottom of the tank, the area of the liquid–gas interface is larger than the value of the vertical installation. $m_s$ and $m_s/m_w$ are both larger than the vertical installation values.
X Direction Sloshing on the Horizontal Installation with PMD

Horizontal sloshing of the tank occurs during attitude control after the satellite enters orbit. The residual fuel in the tank was almost less than 30% of the whole capacity, so filling ratios, including 0.1, 0.15, 0.20, and 0.25, were chosen for the horizontal sloshing test.

X-direction sloshing results on the horizontal installation with PMD are shown in Figs. 19 and 20. The sloshing frequency is related to the increase in the filling ratio. The sloshing damping decreases with an increase in the liquid-filling ratio. The height of the sloshing point changes slightly with an increase in the liquid-filling ratio. The \( h_s \) and sloshing mass increase with an increase in the liquid-filling ratio, and the proportion of the sloshing mass decreases with an increase in the liquid-filling ratio.

When the liquid-filling ratio was increased, the sloshing frequency increased, and the sloshing damping decreased.

The height of the pendulum point changed slightly, and the height of the sloshing center of mass increased slightly with an increase in the liquid-filling ratio.

The sloshing mass increases with an increase in the liquid-filling ratio. The error between the fitted total mass and the weighed total mass was relatively large because the storage tank was placed obliquely in the horizontal direction for the sloshing test in the X-direction and asymmetric along the sloshing direction. Thus, the sloshing mass proportion decreased as the liquid-filling ratio increased.

Conclusions

The sloshing characteristics of a new vane-type propellant tank were studied experimentally. The liquid sloshing performance of the tank was investigated using the resonance-free attenuation sloshing test and forced sloshing test methods. When there was no PMD in the tank, the maximum error in the sloshing frequency was 2.58% compared with the theoretical value. The maximum error of the shaking mass was 6.44%. The maximum error between the \( m_s \) and \( m_w \) was 5.55%. The system’s test results agree considerably with the theoretical results. There is a linear relationship between sloshing frequency and the liquid-filling ratio of the vertical installation test when the liquid–gas interface was in the hemisphere. When the gas–liquid interface was in the cylindrical section, the vertical installation test sloshing frequency remained unchanged. The inverted conical accumulator structure of the PMD can increase the damping in the vertically installed tank. When the liquid-filling ratio was greater than 0.3, the sloshing damping of the vertical installation test remained unchanged. \( m_s \) was linearly related to the liquid-filling ratio when the filling ratio was less than 0.3. The proportion of the sloshing mass had a linear relationship with the filling ratio. The sloshing mass in the vertical direction was less than the result in the horizontal direction. Liquid sloshing results of the vane-type propellant tank will guide the design of spacecraft structures and control systems.

Authors’ Contributions Jintao Liu and Yong Li offered support and guidance. Wen Li, Kun Cai and Lei Chen carried out the experiments. Jintao Liu, Zhen Qu and Nanji Yang wrote the manuscript text.

Funding This work was supported by National Natural Science Foundation of China (Grant No. 52176034).

Availability of Data and Material The data of this article can be obtained by contacting the corresponding author.

Declarations

Competing interests The authors declare no competing interests.
Ethics Approval  Not applicable.

Consent to Participate  Not applicable.

Consent for Publication  Not applicable.

Conflict of Interest  The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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