Research on liquid sloshing performance in vane type tank under microgravity

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Abstract. Propellant management device (PMD) in vane type tank mainly comprises of vane type structure parts, whose performance of restraining liquid sloshing should satisfy spacecraft requirements of high stabilization and fast orbital maneuver. Aiming at liquid sloshing performance in vane type tank under microgravity environment, gas-liquid flow model based on the volume of fluid (VOF) method was put forward, and via numerical simulation liquid sloshing performances of vane type PMD with anti-sloshing baffles and without anti-sloshing baffles in microgravity were analyzed and compared. Simulation results reveal that liquid sloshing performance of vane type PMD with anti-sloshing baffles is markedly superior vane type PMD without anti-sloshing baffles and the baffles make liquid surface become stable fast. Then by comparing between results of microgravity experiments and results of numerical simulations, they are very similar. According to present research, vane type PMD with anti-sloshing baffles has better effects on restraining liquid sloshing and is able to restrain observably propellant sloshing in tanks in order to satisfy spacecraft requirements of high stabilization and fast orbital maneuver.

1. Introduction
The vane type tank is a more advanced propellant tank used in spacecraft, and the inner PMD mainly comprises of vane type structure parts and implements orbital liquid management and control initiatively and full range in the tank. With the continuous development of aerospace technology, the propellant weight fraction in spacecraft continuously expands and the requirement for attitude control accuracy and dynamic stability gets higher, but liquid sloshing in the tank of spacecraft has a bad effect on attitude control and dynamic stability because propellant in the tank may shake violently [1], so the effect of liquid sloshing in tank must be considered. Spacecraft works under microgravity in most life time and liquid sloshing performance in microgravity is markedly different from in gravity, so research on liquid sloshing performance in vane type tank under microgravity becomes especially important. So far space equivalent pendulum model and spring-mass model based on linear theory are usually used to characterise liquid sloshing approximately in engineering, and the models can simulate small amplitude liquid sloshing well, but can’t accurately simulate large amplitude liquid sloshing [2-4]. So in the paper gas-liquid flow model based on the volume of fluid method was put forward and three-dimensional numerical simulation on liquid sloshing in a vane type tank was carried out by using Reynolds Average Navier-Stokes (RANS) and VOF method, then numerical results about liquid sloshing performances of vane type PMD with anti-sloshing baffles and without anti-sloshing baffles in microgravity were analyzed and compared, and results of microgravity experiments and results of numerical simulations were analyzed and compared also.
2. Research technique

Liquid sloshing process in tank is gas-liquid flow process, so in order to solve liquid sloshing process in vane type tank, Navier-Stokes (N-S) equation of gas-liquid flow process was put forward and three-dimensional numerical simulation on the process was carried out by using Reynolds Average Navier-Stokes (RANS) and VOF method. Gas-liquid interface tracking could be achieved by solving fluid volume transport equation, and the effect of surface tension and wall adhesion force is simulated by adding source item to the momentum equation, and data input and output module is founded by using user defined functions (UDF) macro provided by Fluent soft, and real time input of sloshing velocity and acceleration and output of liquid sloshing characteristics and quantization value could be achieved.

2.1. Gas-liquid flow mathematic model based on VOF method

2.1.1. N-S equation. Two-phase N-S equation about transient, incompressible flow, immiscibility, constant temperature and viscosity, and surface tension being are given below.

\[ \nabla \cdot \vec{u} = 0 \]  
(1)

\[ \rho \frac{\partial \vec{u}}{\partial t} + \rho \nabla \cdot \left( \vec{u} \vec{u} \right) = -\nabla p + \nabla \cdot \vec{F} + \rho \vec{g} \]  
(2)

\[ \tau = 2\mu S = 2\mu \cdot \frac{1}{2} \left( \nabla \vec{u} + \left( \nabla \vec{u} \right)^\top \right) = \mu \left( \nabla \vec{u} + \left( \nabla \vec{u} \right)^\top \right) = \mu \Delta \vec{u} \]  
(3)

Where \( \vec{u} \) is velocity, \( \rho \) is fluid density, \( \vec{F} \) is surface tension, \( \vec{g} \) is acceleration, \( \mu \) is fluid viscosity, and \( T \) means transpose. Equation (1) is the continuity equation, and equation (2) is the momentum conservation equation in which the effect on flow by pressure, turbulent flow, surface tension and acceleration is considered.

2.1.2. VOF method. There is an interface between immiscible gas and liquid on which surface tension comes into being because of the difference of intermolecular force between different fluids. Via VOF method gas-liquid flow and interface could be depicted well using a set of N-S equation, it simplifies numerical discription. Two phases gas and liquid exist simultaneously in the arithmetic cells which are at the phase interface, and single phase exist in the cells which are not at the interface. So k-phase volume fraction \( \varepsilon_k \) is introduced, and \( \varepsilon_k \) in a cell can be expressed as:

\[ \varepsilon_k(\text{cell}) = \frac{\iiint_{\text{cell}} \varepsilon_k(x, y, z) \, dx \, dy \, dz}{\iiint_{\text{cell}} dx \, dy \, dz} \]  
(4)

As shown in figure 1, all the cells in the flow can be divided into three areas. If \( \varepsilon_k(\text{cell}) = 0 \) it means k-phase doesn’t exist in the cell, and if \( \varepsilon_k(\text{cell}) = 1 \) it means only k-phase exists in the cell, and if \( 0 < \varepsilon_k(\text{cell}) < 1 \) it means the interface exists in the cell.

![Figure 1. Solution method of gas-liquid interface.](image)

The interface tracking is one of key issues in immiscible multi-phase flow numerical simulation. In order to track the interface, transport equation for each phase volume fraction is put forward below.
\[ \frac{\partial \varepsilon_k}{\partial t} + u_j \frac{\partial \varepsilon_k}{\partial x_i} = S_{\varepsilon_k} \]  

(5)

Where \( S_{\varepsilon_k} \) is used to depict mass transfer between different phases. Because there isn’t mass transfer between different phases in the method, it means \( S_{\varepsilon_k} = 0 \).

\[ \rho = \varepsilon_l \rho_l + (1 - \varepsilon_l) \rho_g \]  

(6)

\[ \mu = \varepsilon_l \mu_l + (1 - \varepsilon_l) \mu_g \]  

(7)

Where subscripts \( l \) and \( g \) each separately represent liquid phase and gas phase.

Practical interface structure under the flow is very complicated, especially exact solution about interface curvature and surface tension in three-dimensional space is very difficult, but Brackbill et al solve this difficult problem by using relatively simple continuum surface force (CSF) model [5], and it is most important that CSF model can be easily extended to three-dimensional space and computational quantity increases a little. Then via CSF surface tension as volume force can be add to the momentum conservation equation, and surface tension can be expressed as:

\[ F = \int_{\partial V} \sigma \mathbf{n} \cdot \hat{\mathbf{x}} (\hat{\mathbf{x}} - \hat{x}) dS = \sigma \mathbf{k} \nabla F \]  

(8)

Where \( k \) is surface curvature, \( \sigma \) is surface tension coefficient, and \( F \) is liquid volume fraction.

2.2. Numerical method

2.2.1. Computational grid model. All the inner space of the tank is used as computational domain for studying liquid sloshing process in vane type tank. In order to simplify calculation, the inner structures such as propellant acquisition vanes (PAV) and propellant refillable reservoir (PRR) are striked off, and anti-sloshing baffles are preserved. As shown in figure 2, the computing grids of all the domain are hexahedron grids based and five surface body grids as a supplement, and total grid number is approximately one million and the ratio of five surface body grids is less than 5%. In order to increase computational accuracy, hexahedron grids should be used in the computational domain where surface tension effects obvious, and grid scale near the wall is defined between 0.5mm and 4mm, meanwhile grid independence is validated.

![a) Computational domain](image1)

![b) Computational grid](image2)

![c) Grid of anti-sloshing baffles](image3)

**Figure 2.** Computational domain and grid.

2.2.2. Initial condition. The simulation on liquid sloshing process in tank is based on liquid surface steady state, so the liquid steady state of reorientation process in microgravity is used for the initial condition of numerical simulation on liquid sloshing in tank, and liquid filling ratio is 40%, as shown in figure 3. Then liquid sloshing process under the non-along orbit condition in vane type tank is numerically simulated and the effect of anti-sloshing baffles on liquid sloshing performance is analyzed. Boundary condition of all the walls is infinitely smooth and no slip, and the solid wall adsorption on gas-liquid interface is simulated by using static contact angle which is set as 1° and the
flow near solid walls of structure is simulated by using standard wall function. Propellant MON is 
chosen as the liquid and the microgravity acceleration is $1 \times 10^{-5} \text{g}_0$ and follows negative Y axis 
direction. Meanwhile the initial point of non-along orbit condition is set as the initial point of liquid 
sloshing numerical simulation, and the non-along orbit condition makes the tank keep shaking for 15s 
which is mainly expressed in the changes of angular velocity on X axis and linear velocity on Y axis 
and Z axis, as shown in figure 4.

![Figure 3. Initial distribution of liquid surface in tank.](image)
![Figure 4. The non-along orbit condition.](image)

3. Results and analyses

3.1. Numerical calculation results and analysis

Gas-liquid interface distribution during liquid sloshing process in tank is shown in figure 5, meanwhile 
at the same time the left side view is about liquid sloshing results with anti-sloshing baffles and the 
right side view is about liquid sloshing results without anti-sloshing baffles, and velocity on the 
interface is displayed also. Numerical results reflect that baffles play a role in strengthening the mixing 
of liquid and make the structure of gas-liquid interface become complicated during tank shaking 
process under the non-along orbit condition. After tank shaking starts, the velocity in interface central 
region increases and relatively significant flow arises in the region also, and when they are 4s and 6s 
the flow velocity in the tank without baffles is significantly higher than the tank with baffles. After 
tank shaking stops, in the tank with anti-sloshing baffles, the bubble motion is restricted to the area at 
the top of tank and there is no interface fracture phenomenon on the whole, because anti-sloshing 
baffles play a role in damping and restraining liquid flow. Meanwhile the holes on the baffles are 
propitious to liquid flow between baffles, which makes there is no interface fracture phenomenon 
between baffles, so the holes also play a part in damping. While in the tank with anti-sloshing baffles, 
under the inertial force the bubble firstly moves from the back side to the bottom and then passes 
through the front side and finally moves back to the top area, and during the process liquid interface 
fracture phenomenon comes into being obviously.
Figure 5. Gas-liquid interface distribution during liquid sloshing process.

The effects with anti-sloshing baffles or not on sloshing mass, sloshing force and slosh torque during liquid sloshing in the tank are shown in figure 6, figure 7 and figure 8 respectively. As shown in figure 6, numerical results of liquid sloshing mass changing process indicate that fluctuation ranges of sloshing mass on Y axis and Z axis are both much greater than on X axis. After tank shaking stops, in the tank with anti-sloshing baffles sloshing mass quickly becomes stable and sloshing mass on Y axis becomes stable after 18s and sloshing mass on Z axis becomes stable after 30s, while in the tank without anti-sloshing baffles sloshing mass on Y axis and Z axis still appears obvious fluctuation. So after tank shaking stops, liquid sloshing could be restrained quickly in the tank with baffles, while the velocity of liquid sloshing attenuation descends significantly in the tank without baffles.
As shown in figure 7, numerical results of liquid sloshing force changing process indicate that fluctuation ranges of sloshing force on Y axis and Z axis are both much greater than on X axis. After tank shaking stops, in the tank with anti-sloshing baffles sloshing force quickly becomes stable and sloshing force on Y axis becomes stable after 20s and sloshing force on Z axis becomes stable after 18s, while in the tank without anti-sloshing baffles sloshing force on Y axis and Z axis still appears obvious fluctuation between 20s and 45s, especially on Z axis. So after tank shaking stops, in the tank with baffles sloshing force rapidly decreases and becomes stable quickly because liquid sloshing could be restrained quickly, while sloshing force amplitude is still relatively large and the velocity of sloshing force attenuation descends significantly in the tank without baffles.

As shown in figure 8, numerical results of liquid sloshing force changing process indicate that fluctuation ranges of sloshing torque on X axis is much greater than both on Y axis and on Z axis. After tank shaking stops, in the tank with anti-sloshing baffles sloshing torque quickly becomes stable and sloshing torque on X axis becomes stable after 20s, while in the tank without anti-sloshing baffles sloshing force on X axis still appears obvious fluctuation between 20s and 45s. So after tank shaking stops, in the tank with baffles sloshing torque rapidly decreases and becomes stable quickly because liquid sloshing could be restrained quickly, while sloshing torque amplitude is still relatively large and the velocity of sloshing torque attenuation descends significantly in the tank without baffles.

![Figure 6](image-url)

**Figure 6.** The effects with anti-sloshing baffles or not on sloshing mass.

![Figure 7](image-url)

**Figure 7.** The effects with anti-sloshing baffles or not on sloshing force.
3.2. Comparative analysis between simulation result and experimental result

Figure 9 below shows the contrast between numerical result and experimental result. The comparative analysis indicates that microgravity experimental result and numerical simulation result are very similar, and gas-liquid interface distributions between the two results during sloshing process are much the same and there are both no interface fracture phenomenons. So the validity and reliability of numerical analysis methods in the paper are verified well.
4. Conclusions
Via analysis and research on liquid sloshing performance in vane type tank under microgravity, conclusions below can be gotten.

a) Microgravity experimental result and numerical simulation result are very similar, and the validity and reliability of numerical analysis methods are verified well. Meanwhile numerical calculation can simulate some boundary conditions and microgravity which cannot be simulated by tests and directly give some parameters which can be measured more difficulty in tests, so numerical analysis methods in the paper have great practical value in engineering applications.

b) Vane type PMD with anti-sloshing baffles has better effects on restraining liquid sloshing and is able to restrain observably propellant sloshing in tanks in order to satisfy spacecraft requirements of high stabilization and fast orbital maneuver.

c) Anti-sloshing baffles and these holes on them both effect liquid sloshing in tank significantly, which offer valuable references for the PMD design for restraining liquid sloshing in the subsequent tanks.

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References
[1] Qu G J 2000 Spacecraft Dynamics Engineering (Beijing: Chinese Science and Technology Press) pp 288-289
[2] Kana D D 1988 Validated spherical pendulum model or rotary liquid slosh [R]. American Institute of Aeronautics and Astronautics, JSpRo. 26: 188-195.
[3] Choi J, Sarigul K N 2006 Liquid sloshing in flexible tanks under thruster firing for orbit adjustment [C]. AIAA Joint Propulsion Conference & Exhibit, [s. 1.] AIAA, 9-12.
[4] Mitra S, Sinhamahapatra K P 2007 Slosh dynamics of liquid-filled container withsubmerged components using pressure-based finite element method [J]. Journal of Sound and Vibration, 304: 361-381
[5] Brackbill J U, Kothe D B, Zemach C 1992 A continuum method for modeling surface tension [J]. Journal of Computational Physics, 100: 335-354.