Research on Sinking Movement of Liquid Propellant in Space Vehicle

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Abstract. Considering the requirement of rocket engine restart on the liquid propellant location, this paper dedicates to the simulation research on sinking movement of liquid propellant in space vehicle. The extrusion, thrust and structural types of liquid propellant management for space vehicle are summarized. The numerical simulation and drop tower test are compared to study how the liquid propellant moves in the gravity environment, and the relationship between the sinking time and flight acceleration for a new-type space vehicle are provided. These results have considerable significance for the liquid propellant management and acceleration design of space vehicle.

1. Introduction

With the rapid development of aerospace technology and space military demand, various new space vehicles are being developed to seize the space interests and the initiative of future wars. New space vehicles represented by the United States X-37B and X-51 will be able to perform complex missions in outer space, earth orbit space, sub-orbital space and airspace in the near future, including orbit transfer, detection, reconnaissance, strike and so on [1-2].

Complex flight trajectory requires that the power system of the new space vehicle can restart the engine many times according to the requirements of mission and control. However, in the microgravity environment after engine shutdown, the liquid propellant will present complex spatial motion in the tank. Once the propellant delivery port is exposed to the pressurized gas in the tank when the engine restarts, it will cause the propellant entrained air, which will affect the engine start, and even cause the engine structure damage and explosion [3-4]. Therefore, the management of liquid propellant before restart of power system is of great significance to enhance the safety and maneuverability of spacecraft, which is one of the key technologies for the development of new spacecraft.

In order to ensure the liquid propellant can cover the conveyor port at the tank’s bottom when the engine starts, many sinking management types of liquid propellant for spacecraft are applied, such as the extruded type, the forward push type and the tank structure scheme [5]. Extruded propellant management uses high pressure gas to extrude liquid propellant into engine by designing metal or non-metal film in tank. It is often used in cruise missiles for short flight. However, due to the compatibility and fatigue between film and propellant, this method is not suitable for low temperature propellants such as liquid hydrogen and liquid oxygen. The film extrusion propellant supply tank is shown in Figure 1. Forward propellant management uses the overload generated by the thrust of small solid
rocket or attitude control engine to sink liquid propellant into the conveyor port. It is mainly applicable to the sinking management of medium and large liquid rockets, such as Saturn V in USA (as shown in Figure 2), Ariane-5 in Europe, H-2A in Japan and Long March-3 in China. Tank structured propellant management uses mechanical conveyors, current storage devices or compartments to ensure liquid propellant sinking. The design of piston, collector and other devices is common in liquid rocket and missile in 1950s (as shown in Figure 3), while the design of multilayer compartment combined with one-way valve is adopted in American space shuttle and X-34 aircraft. However, the structure and executing mechanism of tank-structured propellant management are complex and heavy.

With the well development and successful application of liquid hydrogen and liquid oxygen cryogenic propellant technology in the field of space transportation and weapon equipment, and the increasing size of space vehicles, the design of forward liquid propellant sinking management has become an important factor to improve the maneuverability of new space vehicles. The key is to design reasonable boost overload and fuel consumption to ensure that liquid propellant sink to the bottom and cover the conveyor port in a certain time after overcome the surface tension and sloshing effects. Larger thrust will increase fuel consumption and reduce payload, while smaller thrust will not meet the sinking needs. Therefore, the analysis of the sinking process is very important to ensure the smooth restart of the spacecraft engine, which can provide important reference for the selection and design of bottom sinking boost.

In this paper, the Volume of Fluid [6-8] (VOF) method is used to simulate the motion of liquid propellant under overload conditions for the scaled model of American Centaurus Liquid Hydrogen
Tank. The reliability and accuracy of the numerical simulation are verified by the drop tower test results. Then, according to the flight mission characteristics of a space vehicle, the relationship curves of settling time of liquid oxygen propellant under different overload conditions are obtained, which provides an important reference and basis for the selection and design of bottom sinking boost.

2. Liquid motion simulation under overload condition

The volume of fluid (VOF) method is a Euler numerical method for free surface tracking, in which the free surface variation is described by tracking the volume fraction of the mesh element occupied by the fluid volume. When the ratio of fluid volume to mesh volume is 1, the mesh is filled with fluid, when the ratio is 0, the mesh does not contain fluid, and when the ratio is between 0 and 1, the mesh contains free surface.

When it is assumed that the fluid is incompressible viscous flow and its flow pattern is laminar flow, then the fluid continuity equation, momentum equation and volume function conservation equation of fluid motion process can be expressed respectively as follows:

$$\nabla \cdot \vec{V} = 0$$

$$\rho \left( \frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V} \right) = -\nabla p + \mu \Delta \vec{V} + \rho \vec{a} + \vec{F}_s$$

$$\frac{\partial f}{\partial t} + \vec{V} \cdot \nabla f = 0$$

(1)

where, \( \vec{V} \) is the velocity, \( \rho \) is density, \( p \) is pressure, \( \vec{a} \) is overload, \( \mu \) is kinematic viscous coefficient, \( f = f(x, y, z, t) \) is volume function and \( \vec{F}_s \) is equivalent volume force form of surface tension of fluid. The surface tension of the fluid is calculated using the Continuous Surface Force (CSF):

$$\vec{F}_s = \sigma k \nabla f$$

(2)

Where, \( \sigma \) is the surface tension coefficient of the fluid and \( k \) is the interfacial curvature.

In addition, when it is assumed that the boundary condition of fluid motion is that the velocity of fluid motion satisfies the non-slip condition on the wall of the tank and that the fluid and the wall of the tank are completely infiltrated, the following equations hold:

$$\begin{align*}
\n\vec{V} &= 0 \\
\theta &= 0
\end{align*}$$

(3)

In order to analyze the liquid propellant moving process of the American Centaurus Liquid Hydrogen Scaled Tank [9-11] under overload conditions, the 3D modeling and simulation analysis were carried out by using the VOF method of FLUENT software. The scaled tank has a cylindrical section in the middle and two revolving ellipsoids with 11cm long axis, 1.38 long and short axis ratio at the top and bottom. The tank height is 21.8 cm and the radius is 5.5 cm. The established 3D mesh distribution is shown in Figure 4.

Figure 4. The Scale Model and Its Mesh Distribution of American Centaurus Liquid Hydrogen Tank

The liquid volume of American Centaurus Liquid Hydrogen Scaled Tank is 70%, and the initial distribution of liquids is shown in Figure 5. In this state, the liquid is all located at a front bottom away from the bottom transfer port of the tank. The liquid propellant sinking is considered under the
overload conditions, the simulation analysis is carried out, and the moving process is shown in Figure 5.

![Figure 5. The liquid moving process of American Centaurus Liquid Hydrogen Scaled Tank](image)

It can be seen from Figure 5 that the liquid propellant sinking movement under overload mainly includes 6 typical process states:
1) $T_1=0\text{s}$, initial state of liquid propellant;
2) $T_2=0.51\text{s}$, the liquid flows back from the front bottom along the wall surface of the tank and contacts the back bottom;
3) $T_3=0.61\text{s}$, the liquid flows from the back bottom edge to the center and squeezes each other to form upward liquid flow;
4) $T_4=0.76\text{s}$, the liquid flow moves upward to reach the gas-liquid interface;
5) $T_5=1.11\text{s}$, the liquid flow continues to move upward to the top bottom of the tank;
6) $T_6=2.82\text{s}$, the liquid flow falls back, the front bottom is occupied by the gas, and then the liquid sloshing at the back bottom until it is stable.

The comparison between 3D simulation analysis results by VOF method and drop tower overload test of American Centaurus Liquid Hydrogen Scaled Tank is shown in Table 1. It can be seen from Table 1 that the maximum error is 11%, which can meet the requirement of the design of propellant sinking management. The reliability and accuracy of the numerical simulation of liquid motion in spacecraft tank using VOF method are verified.

| Table 1. Comparison of simulation and test results of liquid moving process |
|-----------------------------|-----------------|--------|--------|--------|--------|
|                            | T1(s) | T2(s) | T3(s) | T4(s) | T5(s) | T6(s) |
| Numerical simulation       | 0     | 0.51  | 0.61  | 0.76  | 1.11  | 2.82  |
| Drop tower test            | 0     | 0.46  | 0.58  | 0.71  | 1.04  | 2.68  |
| Error ratio                | -     | 11 %  | 5 %   | 7 %   | 7 %   | 5 %   |

3. Motion Analysis of Liquid Sinking for Space Vehicle
Compared with traditional launch vehicles and missile weapons, new space vehicles perform more complex maneuvering flight and steering adjustment. The mission profile of a new type of spacecraft is shown in Figure 6. The boost stage is separated when the high thrust booster rocket reaches a certain height, and the aircraft leaps and turns in the air by using the liquid oxygen kerosene engine, then returns to the primary launch site to complete the whole flight task.
In the flight mission, the aircraft needs to undergo the process of drastic changes in flight overload, which includes boost stage separation, inertial landing, jump flight, air steering and attitude adjustment, descent and return field, etc. Especially in the flight stage when the propellant margin is small and the engine shuts down to restart, due to the inertia of aerodynamic drag and attitude adjustment, the liquid propellant will produce intense motion in the tank, exposing the conveyor port to the pressurized gas. Therefore, in order to ensure the normal restart of the liquid oxygen kerosene engine, it is necessary to analyze and predict the liquid movement process in the propellant tank, and obtain the relationship between overload and sinking time, which provides important reference for the control and power system design.

For the sinking motion of propellant during the jump flight and the attitude adjustment in the liquid oxygen tank of the spacecraft in Figure 7, the 3D fluid model based on VOF method is used to simulate and analyze the sinking motion. The length and radius of the straight section of the tank are 7 m and 1.44 m, and the depth of the front and back bottom of the tank is 0.4 m. During the process of aircraft steering and attitude adjustment, liquid oxygen flows along the side wall of the tank to the front bottom due to centrifugal force and overload. The distribution of liquid oxygen propellant in the tank is shown in Figure 8 at the initial moment after turning.

With the liquid oxygen propellant distribution at the initial time after the spacecraft's steering and attitude adjustment as the initial condition, if the propellant sinking control is not carried out, that is,
there is no flight overload to cause the liquid sinking, the distribution of liquid oxygen in the tank in
the next 20 seconds is shown in Figure 9.

![Figure 9. Distribution of liquid oxygen propellant in tank in 20s](image)

(a) 5s  (b) 10s  (c) 15s  (d) 20s

It can be seen from Figure 9 that when the liquid oxygen propellant is free to move, its distribution
in the tank will become confusing. The propellant delivery port on the back and bottom of the tank is
always exposed to the pressurized gas. At this time, the liquid oxygen kerosene engine ignition may
lead to the engine abnormal work or even explosion.

When an axial 1g overload is applied to the liquid oxygen propellant distribution state shown in
Figure 8, the distribution state change process is as shown in Figure 10. The liquid oxygen first flows
along the wall surface to the rear bottom, and then rushes from the other side wall surface due to
inertia. The process is repeated until the kinetic energy is consumed and sloshing to stop, the liquid
propellant covers the transfer port, and bubbles in liquid are gradually precipitated.

![Figure 10. Distribution state change process of liquid oxygen propellant after 1g overload](image)

(a) 1.5s  (b) 3s  (c) 4.5s  (d) 6s

When the sinking time is defined as the time span from the initial time to the time when the liquid
oxygen propellant completely covers the rear bottom ports without air entrainment and the sloshing is
stable. The relationship between sinking time and sinking overload can be obtained by applying
different sinking overload to the distribution state of liquid oxygen propellant shown in Figure 8, and
the result is shown by the solid line in Figure 11. In addition, since the consumption of the sinking
booster fuel is proportional to the sinking overload and the sinking time, the equivalent consumption
curve of the sinking booster fuel can be obtained as shown by the dashed line in Figure 11.

![Figure 11. The relationship between settling time and overload of liquid oxygen propellant](image)
It can be seen from Figure 11 that a larger sinking overload can cause the liquid oxygen propellant to sink faster, but consume more sinking boosting fuel. Smaller sinking overload is more economical, but the sinking time is longer. Therefore, the sinking overload needs to be determined according to the flight mission and maneuverability design requirements of the aircraft. The above results can provide important reference for the overall capability, attitude control and ballistic design of the new space vehicle.

4. Conclusions
Liquid propellant sinking movement in the tank of space vehicle is studied in this paper. The VOF method based liquid motion simulation under overload condition is developed. The reliability and accuracy of the VOF based method to simulate the sinking process under overload is verified by comparing simulation results with the results of the drop tower overload test of American Centaurus Liquid Hydrogen Scaled Tank. The sinking time of the propellant under different overload conditions is obtained according to the initial distribution of the liquid oxygen propellant of a spacecraft after air steering and attitude adjustment. The results indicate that smaller sinking overload has more economical sinking boost propellant consumption, but requires longer sinking time. Therefore, in the design of the engine restart after the spacecraft undergoes severe overload changes and attitude adjustment, it is necessary to comprehensively consider the influence of sinking time, fuel consumption, ballistics and other factors to determine the sinking management scheme of the liquid propellant. The research results and methods on the sinking movement of liquid propellant in this paper can be widely used in the design of launch vehicle, missile weapon and new space vehicle using liquid propellant.

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