Research on a new open water-brake method for double-track rocket sled test

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Abstract. Aiming at the problem of water-brake recovery for double-track rocket sled, an open water-brake method based on U-groove structure was proposed and the structural model was established. Under the condition of commonly used requirements, the brake effect was evaluated through the classic fluid mechanics theory, and the brake efficiency and safety were studied using two analytical methods of fluid-structure interaction and statics. The results showed that the open water-brake method was feasible in principle. Compared with the water bucket, the open brake device had the advantages of simple structure and convenient processing, and the phenomenon of water blockage would not occur and affect the brake efficiency and test safety. At the same brake speed, the open brake device could generate higher brake force. Recommendations for follow-up work were given before the open water-brake method was officially put into use.

1. Introduction
Rocket sled is a very effective large-scale ground dynamic test method between laboratory test and full-scale flight test, which mainly simulates the environment such as speed, acceleration and Reynolds number of aircraft, missiles and space vehicles. The non-destructive recovery test is an important type of rocket sled test through different braking methods.

Depending on the speed, quality and structure of the test system, different forms of braking methods can be used in the rocket sled test. At present, there are mainly the following mature methods at home and abroad: drag parachute brake, sand brake, resistance plate brake, arresting cable brake, reverse thrust rocket brake and water-brake, etc. Hanging parachute and shooting parachute are the two main method of parachute brake, and the rocket sled is decelerated by the aerodynamic resistance formed by the drag parachute hooked on the sled. The sand brake slows the rocket sled through the resistance generated by the solid probe mounted on the rocket sled into the sand pre-placed between the two tracks. For resistance plate brake, the aerodynamic drag plates installed on both sides of the rocket sled expand at the predetermined position, which increase the windward area to reduce the speed of the rocket sled. The arresting cable brake slows the rocket sled by the water flow resistance, which is generated by the rocket sled hooking the cable placed on the track and driving the piston to move in the conical tube filled with water, to consume the kinetic energy of the rocket sled. The reverse thrust rocket brake makes the rocket sled speed decrease rapidly by igniting the reverse thrust rocket when braking is required. The principle of water-brake is that the high-speed rocket sled meets the static water, and the kinetic energy of the rocket sled is converted into the kinetic energy of water through the momentum exchange, so that the speed of the rocket sled is rapidly reduced [1]. Among
the above methods, water-brake is widely used in rocket sled test at home and abroad due to its economic, reliable, flexible and large braking capabilities [2].

2. Principle of water-brake
The water-brake recovery system consists of a brake device and a statically placed water. The brake recovery device is installed on the rocket sled, and the water is poured into the trough of the track bearing beam in a free state, or filled in a plastic water bag and placed on top of the track. The water-brake device intersects with the still water when the rocket sled runs to the braking section at high speed. In this process, the water obtains a speed with a predetermined direction (depending on the parameters of the braking device) and a certain magnitude (depending on the intersection speed and the characteristics of the braking device) from the stationary state, while the momentum of the rocket sled is converted into the momentum of water, and the rocket sled obtains a strong brake force. The principles of momentum conservation and energy conservation are satisfied in the process of water-brake. When the energy loss due to aerodynamics and friction is ignored, the brake model is shown in Formula (1).

\[
\begin{align*}
    m_{\text{rocket sled}} v_{\text{rocket sled}}^+ &= m_{\text{rocket sled}} v_{\text{rocket sled}}^- + m_{\text{water}} v_{\text{water}}^- \\
    \frac{1}{2} m_{\text{rocket sled}} v_{\text{rocket sled}}^2 &= \frac{1}{2} m_{\text{rocket sled}} v_{\text{rocket sled}}^2 + \frac{1}{2} m_{\text{water}} v_{\text{water}}^2
\end{align*}
\]  

(1)

3. Types of water-brake method
Water-brake methods of rocket sled have a longer development time, higher technical maturity, and rich engineering experience. According to the different types of rocket sled, the water-brake device of monorail and double-track rocket sled are divided.

3.1. Water-brake device of monorail rocket sled
The monorail rocket sled is not suitable for large water bucket because of compact space and poor stability. The brake method of impacting water is often used for braking. Figure 1 shows the simple brake device for monorail rocket sled. The brake device designed as a spike-shaped structure is installed above the first slipper of the rocket sled, and some troughs made of polystyrene material with an ‘H’-shaped cross section are placed on top of the track, and the static water as the braking medium is poured into the troughs. During the test, when the high-speed rocket sled meets the water, the troughs are split by the split structure, and the still water is sprayed to both sides at a certain speed through the guide surface. The rocket sled is decelerated through momentum exchange.

![Figure 1. Simple brake device of monorail rocket sled.](image1.png)

The brake method of impacting water has the advantages of simple brake device, small space occupation and convenient implementation, but has the disadvantages of low braking force level and
uncontrolled water flow. In order to obtain a high level of braking force on a monorail rocket sled, a horizontal momentum exchange water bucket was developed in China, as shown in Figure 2. The water inlet of the monorail rocket sled water bucket is located directly above the first slipper, and the still water (packed in plastic bags and placed on polystyrene support plates with U-shaped groove) placed on top of track is used as the braking medium. To a certain extent, this type of water bucket improves the brake force of the monorail rocket sled.

3.2. Water-brake device of double-track rocket sled

Usually the water bucket is used as brake device in double-track rocket sled. According to the direction of water flow during the braking process, the water bucket of the double-track rocket sled can be divided into two types: the horizontal momentum exchange type and the vertical momentum exchange type. The still water can be picked up by the horizontal momentum exchange water bucket, and sprayed horizontally to both sides of the rocket sled. Figure 3 shows the ‘V’ shaped water bucket used in Russia. The vertical momentum exchange water bucket has the same principle, the difference is that after the vertical plane diversion, the water is sprayed vertical above the rocket sled. Figure 4 shows the domestically developed vertical momentum exchange water bucket, which is installed on both sides of the double-track rocket sled, and the brake medium water is placed above the track.

![Figure 3. V-shaped water bucket.](image1)

![Figure 4. Vertical momentum exchange water bucket.](image2)

The brake force generated by the water bucket has the advantages of easy adjustment and control, high brake force level and reliability. However, the water bucket has the disadvantages of complicated internal structure, difficult processing, high cost, and difficulty in detecting internal defects.

4. Analysis of the open water brake method

In view of that water-brake is used frequently in rocket sled tests, it is helpful to enrich the brake methods and expand the rocket sled test field by studying a new water-brake method with a relatively simple structure, low cost, easy installation and operation, and high level of brake force.

4.1. Open U-groove brake device

The U-shaped groove braking device, whose main body was curved channel, was welded by steel plates and installed at the front of the rocket sled. The channel had a 1000mm inlet radius, 45° inlet angle, 500mm outlet radius, and 135° outlet angle. The water inlet of the channel was processed into a 120° sharp split shape, which was more easily to damage the water dividers in the trough that separate water of different heights. Deflectors with a height of 150mm were designed on both sides of the channel to restrict the direction of water flow. Considering that the brake process would form a brake force of tens of tons, the load-bearing structure of the brake device was an integral beam formed by square steel. The water inlet and outlet of the device were both at a certain height from the rocket sled chassis, and a large torque would be formed during braking. In order to ensure that the device had sufficient rigidity, the supporting structures were designed on the side and the back. Figure 5 shows the structure of the U-groove brake device.
4.2. Numerical simulation of brake process

The brake process of the device was analyzed through fluid-structure interaction method, mainly including pre-processing using Hypermesh for mesh division, post-processing using LS-PrePost, and Numerical simulation using finite element method (FEM) coupled Smoothed Particle Hydrodynamics (SPH) [3]. Fluid-structure interaction analysis conditions included brake speed of Ma 0.4, brake medium of water, water area of 0.25m × 0.15m × 5m (lateral × vertical × heading), and the cross-sectional area (formed by the intersection of the brake device and water) of 0.01136m² [4]. The water area material adopted the EOS_GRUNEISEN state equation, as shown in Formula (2).

\[
p = \frac{\rho C^2 \mu \left(1 + \left(1 - \frac{\gamma_0}{2}\right) \mu - \frac{a}{2} \mu^2\right)}{\left(1 - (S_1 - 1) \mu - S_2 \frac{\mu^2}{\mu + 1} - S_3 \frac{\mu^3}{(\mu + 1)^2}\right)} + \left(\gamma_0 + a \mu\right)E \tag{2}[5]
\]

Where \(C\) is the shock wave velocity, \(S_1, S_2\) and \(S_3\) are the slope coefficients of the Us-Up curve (shock wave velocity-post wave particle velocity curve), \(\gamma_0\) is the Gruneisen constant, \(\mu = \rho / \rho_0 - 1\), and \(a\) is the first-order volume correction for \(\gamma_0\) [6]. The parameters are shown in Table 1.

| Density (kg m⁻³) | C   | S₁   | S₂   | S₃   | \(\gamma_0\) |
|------------------|-----|------|------|------|-------------|
| 998              | 0.148 | 2.56 | -1.986 | 0.2268 | 0.5         |

Figure 5. The structure of U-groove brake device.

Figure 6. Process image of fluid-structure interaction simulation.
When analyzing the SPH particles and the Lagrange units, a penalty function-based contact method was used, which was equivalent to setting a normal spring at the contact interface. The SPH particles would be subjected to the force of the spring in the opposite direction when they were to penetrate the Lagrange units, thereby contact effect would be achieved [8]. Figure 6 shows the analysis process of the fluid-structure interaction.

Figure 7 shows the analysis result of fluid-structure interaction. The water flow is sprayed from the water outlet at 9ms, the brake force converged and stabilized to about 30 tons at 12ms. During the whole process, the stress of the brake device below the water surface is high, and the average stress level is below 500MPa. The first group of slippers has higher stress due to the overturning torque caused by the brake force, but the rocket sled deformation is less than 2mm.

4.3. Theoretical evaluation of brake effect

When the water flow passed through the U-groove brake device, it was simplified to the impact of the free jet water on the channel. Figure 8 shows the channel structure of brake device. The brake effect was theoretically evaluated using the formula of free jet impact force in classical fluid mechanics, such as Formula (3).

\[
F_U = \rho_{\text{water}} \cdot qV \cdot v (1 - \cos \theta)
\]  

(3)

In the formula, \(qV\) was the flow rate of the fluid, which was expressed as \(A_{\text{water}} v\) when the brake force was calculated, where \(A_{\text{water}}\) was the cross-sectional area of the intersection of the brake device and water, and \(v\) was the speed of the rocket sled. The result calculated by Formula (3) was the ideal braking force, without considering the energy loss. During the test, there would be energy loss when the water flowed through the brake device, which was mainly reflected in the reduction of the water flow speed at the outlet. For this reason, the Formula (3) was converted into the Formula (4) through a special coefficient.

\[
F_U = \rho_{\text{water}} A_{\text{water}} v^2 (1 - R_v \cos \theta)
\]  

(4)

Where \(v\) was the rocket sled speed or water flow rate into the device, and \(v=136m/s, R_v\) was the flow rate ratio of the outlet to the inlet. According to the test data of the United States, \(R_v=0.8\) [9]. According to the experimental research results of Wuhan University of Hydraulic and Electrical Engineering, \(R_v=0.66 \sim 0.81\) [1]. \(\rho_{\text{water}}\) was the water density. \(A_{\text{water}}\) was the cross-sectional area of

![Figure 7. The brake force curve.](image)

![Figure 8. The Channel structure of brake device.](image)
the intersection of the brake device and water, and \( A_{\text{water}} = 0.01136 \text{m}^2 \). \( \theta \) was the outlet angle, and \( \theta = 135^\circ \).

When \( R_s = 0.8 \) was taken, the brake force could be calculated as \( F_u = 328973N \), which was basically consistent with the result of fluid-structure interaction analysis. The general brake force formula, which was based on the water medium and took intersection height and brake speed as variables, could be obtained by appropriate conversion of the intersection cross-sectional area, as shown in Formula (5).

\[
\begin{align*}
F_u &= 2471h^2v^2 & (h \leq 0.082) \\
F_u &= 2471 \times 0.082v^2 + 392(h - 0.082)v^2 & (h > 0.082)
\end{align*}
\]

Where \( h \) was the height of the water entering the brake device.

4.4. Brake device safety analysis

The safety of the rocket sled structure was affected by the harsh impact environment generated during the brake process. When the strength of the device was insufficient, it would cause structural failure and test accident. When the rigidity of the device was insufficient, it would cause structural deformation and affect the brake force level. The safety of the brake device was evaluated by static strength analysis of the braking process. The static strength analysis conditions were: full constraints were imposed on the slippers, 8g of horizontal and vertical vibration accelerations and gravity acceleration were loaded on the entire system, 33 tons of heading brake force was loaded on the brake device, 9267N of aerodynamics force was loaded on the corresponding parts [10]. Figure 9 and Figure 10 show the stress and deformation results of static strength analysis.

![Figure 9. Stress result of static strength analysis.](image)

![Figure 10. Deformation result of static strength analysis.](image)

According to the stress analysis result of static strength, the overall stress of the brake device was less than 340Mpa, far lower than the allowable stress of the material. The stress of integral beam was slightly higher but not more than 500MPa, and the material should be high-performance steel. The stress level of the rest was low. The static strength of the structure met the requirement of the test.

According to the results of the deformation analysis of the static strength, it was acceptable that the deformation was about 4mm at the water inlet and below 4mm at the rest. The change of the brake force caused by the deformation of the device was evaluated using Formula (5), and it was found that the brake force was increased by 10151N, which increased the brake force by about 3.1%, and the structural safety would not be affected.

5. Conclusions

The following conclusions were obtained through the aforementioned analysis.

(1) Water blockage might occur in the closed water channel of the water bucket, because the water and air entered the water channel at the same time, the mixing of water and air caused the cross-
sectional area of the channel to be smaller than the actual cross-sectional area of the aerated water flow. The water blockage would cause two results. First, the amount of water entering the channel was greatly reduced, so that the brake force of the bucket was significantly reduced. Second, the pressure inside the bucket increased, causing the waterway to tear and the test to fail [11].

(2) The braking force formula of the domestic V-shaped horizontal momentum exchange bucket \( (\theta=105^\circ) \) was \( F_p = 726h^2v^3 \). Under the premise of ensuring structural safety, the brake efficiency ratio of U-groove brake device and V-shaped water bucket was 3.4~2.25 when the intersection height was 0~190mm. U-groove brake device could provide higher brake force.

(3) Stresses not exceeding 340 MPa were safe for steel braking devices when the braking speed was 136 m/s. By optimizing the structure of the stress concentration location, the stress value could be reduced. The deformation of the device was small and the contact conditions were stable, which proved that the structural design of the device was reasonable.

(4) The large turning moment of the chassis was caused by the large water flow angle because the water inlet and outlet of the U-groove brake device were far away from the chassis. When higher brake force was needed, it was necessary to increase the rigidity of the chassis by strengthening the device connection and support structure.

(5) The rocket sled would be covered by the water mist environment sprayed by the brake device installed at the front, so it was necessary for the rocket sled to have adaptability to the water mist environment [12].

(6) The numerical simulation analysis of the open water-brake method proves that the principle is feasible. Before formal use, it is necessary to carry out corresponding verification tests to obtain the consistency of simulation and actuality. At present, the test verification is underway.

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