The Mars parachute flight environment is supersonic, low-density, and low dynamic pressures. To ensure the operating performance and reliability, the design optimization and verification of the Tianwen-1 Mars parachute have been carried out. Firstly, through supersonic and subsonic wind tunnel tests, the design optimization of the parachute structure is realized. Subsequently, the high-altitude flight tests of four parachutes were conducted, the drag coefficient and the oscillation angle of the parachute from supersonic to subsonic speed were gained, and the aerodynamic characteristics and reliable opening of the parachutes were thoroughly tested and verified. This article presents the design, development, and qualification of the Tianwen-1 Mars parachute, which can provide a reference for the creation of future Mars exploration parachutes.

1. Introduction

China’s Tianwen-1 Mars probe successfully landed on the Utopia Plain at 7:18 a.m. Beijing Time, on 15 May 2021 [1]. The success rate of Mars missions is about 50%, and most failures occur during the entry, descent, and landing (EDL) phase [2]. Parachutes of low-density supersonic play a vital role in the EDL of Mars and directly determine the success of the entire mission.

Generally, the disk-gap-band (DGB) parachute has been primarily employed in the Mars exploration missions to date [3]. The DGB designs utilized for the successful missions to Mars fall into three evolutionary phases, an initial Viking design, modified designs for MPF (Mars Pathfinder) and MER (Mars Exploration Rover), and a return to the Viking geometry for the Phoenix, MSL (Mars Science Laboratory), and Insight and Perseverance [4]. To verify the deceleration and stability under the Mars conditions, numerous wind tunnel tests [5, 6], low-altitude subsonic drop tests [7], and high-altitude flight tests [8–11] have been performed for Mars missions [12, 13].

From the 1960s, a series of supersonic flight tests, including the Planetary Entry Parachute Program (PEPP), the Supersonic Planetary Entry Decelerator Program (SPED), and the Supersonic High-Altitude Parachute Experiment (SHAPE) aimed at maturing supersonic decelerators for the Mars Viking Project, have been conducted to confirm the inflation characteristics in low density and high Mach-number conditions [14–16].

The first DGB used at Mars, on the Viking missions, leveraged heavily from design aspects of the preceding PEPP, SPED, and SHAPE tests. The Viking parachute is a DGB parachute with geometric porosities of 12.5 percent. Wind tunnel testing was conducted to finalize the parachute system configuration. The testing results show that the increase in the ratio of the suspension line length to the canopy diameter from 1.0 to 1.7 increased the parachute’s drag coefficient.

The airbag landing system of Mars Pathfinder (MPF) placed stability requirements on the parachute that could not be met with a canopy of the geometry flown by Viking. Thus, the Viking DGB parachute was modified to increase the length of the band to improve stability, and the MPF parachute is a DGB parachute with geometric porosities of 12.5 percent [17–19]. Qualification of the MPF parachute was conducted through wind tunnel tests and low-altitude flight tests.

Recently, the Low-Density Supersonic Decelerator (LDSD) supersonic flight tests were conducted to develop the supersonic disk-sail (SSDS) and the supersonic ring-sail (SSRS) parachutes based on the MSL parachute [20, 21]; however, the newly developed parachutes failed in each
flight test. Subsequently, the Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) project was conducted as a risk reduction activity for the Mars 2020 mission [22–24]. This leads to a critical need to better understand the dynamics of the supersonic parachute inflation in a Mars-like environment [25].

Using the heritage data from the previous Mars parachute system, a new DGB parachute was selected as the candidate for Tianwen-1. The parachute was performed through wind tunnel and high-altitude flight tests. This paper describes the design and qualification of the Mars parachute system of Tianwen-1, which can provide references for the development of parachutes for subsequent deep space exploration missions.

2. Parachute Design

2.1. Mars Parachute Type Analysis and Selection. The Mars parachute opening flight is characterized by supersonic speed, low density, and low dynamic pressure [26]. In addition, atmospheric activities, such as the Martian vortex activity and dust devil, may cause harsh parachute opening conditions [27]. Compared with the parachute working on earth, the parachute of the Mars lander faces more problems such as difficulty in parachute opening, unstable inflation, and decreased drag coefficient during working. Therefore, it is necessary to investigate various parachute opening and working performances under supersonic conditions [28].

From the 1960s, the United States carried out various wind tunnel tests and airdrop tests. And three types of parachutes, such as the DGB parachutes, the cross parachutes, and the improved ringsail parachutes, worked under supersonic, transonic, and subsonic conditions [29, 30]. The parachutes’ inflation characteristics, drag characteristics, and stability have been observed, compared, and verified. From the test results, although the cross parachute has the largest drag area as the opening speed increases, it exhibits more excellent vibration and poor stability. In contrast, the improved ringsail parachute and the DGB parachute work well under a Mach number of 1.9. And the DGB parachute is better than the improved ringsail parachute in terms of inflatable and deceleration performances. When working at supersonic speed and low dynamic pressure, the DGB parachute has better inflatable and deceleration performance than the ringsail parachute [31].

All the foreign landers successfully achieved soft landing on Mars have used the DGB parachute, which has good stability and excellent inflation performance in the supersonic and low-density working environment. Due to its demonstrated high-altitude performance and lower technical risk, the DGB parachute with improved design modifications is selected as the candidate for the Tianwen-1 Mars probe.

The basic structure of the DGB parachute is shown in Figure 1, where $D_v$, $D_D$, and $D_B$ are the diameters of the vent, the disk, and the band, respectively; $H_G$ and $H_B$ are the
height of the “gap” and the “band,” and \( L_s \) is the length of the parachute suspension [5].

According to the ratio of the band area to the entire canopy, the DGB parachutes can be divided into the Viking type (Viking, Phoenix, and MSL) and the MPF type (MPF and MER). The Viking type DGB parachute has a high drag coefficient and weak stability, whereas the MPF and its improved DGB parachute have a smaller drag coefficient but better stability. Before landing, the landers that can adjust the attitude, such as “Viking,” “Phoenix,” and “Mars Science Laboratory,” generally choose the Viking-type DGB parachute, whereas the other landers, which cannot, such as “Mars Pathfinder,” or can only adjust the horizontal attitude for a little, such as “Spirit” and “Opportunity,” generally choose the MPF DGB parachute [3].

### 2.2. Parachute Model.

Two ideas were adopted to optimize and improve the existing DGB parachute structure. One is to increase the drag coefficient. The disk part is thus modified to a structure with a higher drag coefficient, such as the hemisflo parachute structure and the triconical parachute structure. The other is to enlarge the band’s area to increase the parachute’s stability, such as adding a tapered band on the lower skirt of the canopy. The specific parachute structures (Figure 2) are shown in Table 1.

For the MPF DGB parachute, the ratio of the disk area to the band area is about \( 38 : 52 \), and the geometric porosity is between 9% and 10%. The MPF DGB parachute’s main performance characteristic is good stability and a low drag coefficient of about 0.4. For the Viking DGB parachute, the ratio of the disk area to the band area is about \( 52 : 35 \), and the geometric porosity is about 12.5%. The main performance characteristic of the Viking parachute is the high drag coefficient of up to about 0.6, but the stability is poor.

The hemisflo DGB parachute, the triconical DGB parachute, and the tapered DGB parachute are all the improved and optimized types based on the Viking DGB parachute. The drag coefficient of the conventional hemisflo parachute is 0.62–0.77, and the stable oscillation angle is between 10° and 15°. The hemisflo DGB parachute is a combination of the characteristics of the hemisflo parachute and the Viking DGB parachute. The canopy of the disk is modified to a spherical structure, and the central angle of the entire canopy structure is 210°. When the top is full, it tends to be

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**Figure 2: Structures of different DGB parachutes.**

**Table 1: Structural parameters of each parachute.**

| Parachute type    | MPF DGB | Viking DGB | Hemisflo DGB | Triconical DGB | Taped DGB |
|-------------------|---------|------------|--------------|----------------|-----------|
| Disk area ratio   | 0.384   | 0.53       | 0.53         | 0.53           | 0.53      |
| Gap area ratio    | 0.1     | 0.12       | 0.12         | 0.12           | 0.12      |
| Band area ratio   | 0.516   | 0.35       | 0.35         | 0.35           | 0.35      |
| Number of gores   | 20      | 20         | 20           | 20             | 20        |
| \( L_s/D_0 \)     | 1.7     | 1.7        | 2            | 1.7            | 1.7       |
spherical, the bulge of the canopy material at the bottom of the disk is smaller, and the stress distribution in each part of the canopy is more uniform. The ratio of the disk area to the band area of the hemisflo DGB parachute is 53:35, and the geometric porosity is about 12.5% [32].

The drag coefficient of the triconical parachute is generally between 0.80 and 0.96, and the stable oscillation angle is between 10° and 15°. To improve the drag coefficient of the original DGB parachute, the Viking disk part is replaced by three conical surfaces. The ratio of the disk area to the band area of the triconical DGB parachute is 53:35, and the geometric porosity is about 12.5%.

3. Comparison of Parachute Type by Wind Tunnel Test

3.1. Test Conditions. To optimize the structure for the Mars parachute, the subsonic, transonic, and supersonic wind tunnel tests were carried out for the five DGB parachutes in this work to obtain their oscillation angle. The test conditions are listed in Table 2. The test setup for the drag coefficients is shown in Figure 3.

3.2. Drag Coefficient. Figure 4 shows the drag coefficients of the five types of DGB parachutes at different Mach numbers. It can be seen that the drag coefficient of each parachute type generally decreases with the increase of the Mach number, ranging from 0.43 to 0.59. The drag coefficients of the parachutes, except for the hemisflo DGB parachute, decrease at Mach 0.9, which may be caused by the wake of the front strut upstream of the model parachute that has the undesired effect of having slightly reduced the measured magnitudes of the aerodynamic coefficients.

Compared with the parachute based on the Viking DGB, the area ratio of the disk to the band of the MPF parachute is smaller, so the drag coefficient of the MPF-type parachute is relatively low, about 0.4. When the Mach number is 0.21, the maximum drag coefficient of the Viking DGB parachute is 0.59, followed by that of the tapered DGB parachute of 0.55. When the Mach number is 0.90, the hemisflo DGB parachute has a maximum drag coefficient of 0.52, followed by the tapered DGB parachute of 0.50. When the Mach number is 1.98, the maximum drag coefficient of the tapered DGB parachute is 0.47, followed by that of the triconical DGB parachute of 0.46.

In the wind tunnel test, the optical setup of a schlieren imaging system is used to observe and record the parachute and the flow field. The schlieren images of each DGB parachute at Mach 1.9 are depicted in Figure 5. It can be seen from the schlieren images that a detached shock wave is formed upstream of each DGB parachute canopy. And a conical shock structure is generated in the front of the bow shock.

3.3. Oscillation Angle. To evaluate the stability of each parachute, image processing is performed on the wind tunnel test.
videos. And the oscillation angle of the parachute under different conditions is obtained. The oscillation angle shown in Figure 6 is the angle between the parachute symmetry axis and the freestream flow direction. Figure 7 shows the oscillation angles of the five DGB parachutes at different Mach numbers. It can be seen that the oscillation angle of each type of DGB parachute generally does not change significantly with the increase of the Mach number, ranging from 5° to 10°. For different parachute types, the MPF DGB parachute oscillation angle is the smallest, followed by the tapered DGB parachute. The oscillation angle of the triconical DGB parachute under each Mach number is the highest.

Combined with the wind tunnel test results at different Mach numbers to select a parachute with better deceleration and stability performance, the tapered DGB parachute can be the best deceleration parachute for the Tianwen-1.

Figure 5: Flow field schlieren diagram of each parachute under Ma 1.98.
4. High-Altitude Flight Test Verification

4.1. Flight Test Scheme. To demonstrate the capability of full-scale tapered DGB parachutes in Mars flight conditions, four high-altitude flight tests were carried out by sounding rockets in April 2018. The sounding rocket assembly consists of a first stage and an approximately 1280 kg test vehicle. The parachute system was installed at the tail of the test vehicle, as shown in Figure 8. The test flight process is shown in Figure 9.

During the flight, the first stage burned out at altitudes of approximately 17 km~20 km, respectively, the payload section reached apogee between 49 km and 64 km. When the payload got the target dynamic pressure and Mach number, the parachute was mortar-deployed. The deployment, inflation, and supersonic and subsonic aerodynamics of the parachute were analyzed by a suite of instruments, including a high-speed video system trained on the parachute, a set of load pins at the interface of the parachute briddles and the payload, and a GPS and inertial measurement unit (IMU) onboard the payload. After decelerating to subsonic speed, the parachute and payload descended to the test range for recovery.

4.2. Test Architecture. Figure 10 shows a schematic of the parachute configuration after deployment. The relevant dimensions of the parachute-payload system are labeled in the schematic, and their values are also listed in Table 3.

The parachute is a 48-gore DGB with a nominal diameter \( D_0 \) of 15.96 m. The majority of the canopy is constructed using a Nylon fabric with a rated strength of \( \sim 1000 \) N/5 cm. The circumferential reinforcements at the trailing edge of the disk and the band leading and trailing edges are \( \sim 10000 \) N Kevlar webbing, and the reinforcements at the vent are \( \sim 40000 \) N Kevlar webbing [33]. The parachute is built using a cord insertion construction where the suspension lines continue into the radials. The suspension lines are constructed from the 7350 N Kevlar line. The entire packed parachute assembly has a mass of 39 kg. The parachute was tested in the wake of a slender payload whose diameter is approximately a sixth of the 4.5 m aeroshell.

4.3. Analysis of Test Conditions. These tests targeted a specific dynamic pressure at parachute deployment to reach a desired load on the parachute at full inflation. The parachutes were mortar-deployed at dynamic pressures ranging from 100 Pa to 950 Pa and Mach numbers between 2.05 and 2.35. In comparison, the parachute of Tianwen-1 must be able to get opened reliably within the range of Ma 1.6~Ma 2.3 and dynamic pressure range of 250 Pa~850 Pa.

Under the high-altitude opening test conducted on the earth and the actual working conditions of Mars, the Reynolds numbers are both in the order of \( 2 \times 10^6 \).

Table 4 shows the test condition settings of the high-altitude open parachute test. There are four test conditions. Figure 11 shows the height and speed boxes for different working conditions.

(1) Test condition 1 is the nominal working condition of Mars parachute opening

(2) Test condition 2 increases the angle of attack based on the nominal condition

(3) Test condition 3 increases the Mach number and the angle of attack but reduces the dynamic pressure based on the nominal condition

(4) Test condition 4 increases the Mach number, the angle of attack, and the dynamic pressure based on nominal conditions

4.4. Test Article Performance. The results of the four supersonic flight tests are shown in Figures 12–16. Figure 12 is
the time curve of the height of the parachute. After the parachute deployed, the height of the parachute first increases and then decreases, and the test vehicle reaches apogee at approximately 63 km. The parachute drag increases rapidly after deployment, and the speed of the parachute decreases before the apogee of trajectory in Figure 13. As the aerodynamic drag increases further, the parachute gradually decelerates until it reaches about 15 m/s of landing speed.

The parachute drag during the opening process is shown in Figure 14. In the fourth test, the parachute opening load is the largest, 110 kN, and the third test has the smallest dynamic pressure, so the parachute opening load is the smallest, only 39 kN. In the process of a parachute opening, it can be seen that large parachute force oscillations occur after the first inflation peak force, indicating that under the condition of supersonic speed, the projection area of the tapered DGB parachute changes repeatedly, and the parachute canopy undergoes collapse and reinflation cycles. A
A significant contributor to these area oscillations is the interaction between the aeroshell wake and the parachute flow fields [34].

From the parachute opening load and freestream flow parameters, the curve of the parachute drag coefficient with the Mach number can be obtained, as shown in Figure 15.
The test results show that between $Ma_{0.2}$ and $Ma_{2.4}$, the drag coefficient of the tapered DGB parachute increases first and then decreases. The variation range of the drag coefficient is 0.39~0.70. At $Ma_{1.5}$, the drag coefficient reaches the maximum value of about 0.7.

In the wind tunnel test of the drag coefficient, when the parachute is at a Mach number of 0.21, 0.9, and 1.98, the corresponding drag coefficients are 0.55, 0.50, and 0.47, respectively. Except for Mach number 0.9, the drag coefficient in the wind tunnel test is consistent with the results of the high-altitude drop parachute tests. Because parachutes are in the wake of slender bodies in the high-altitude drop parachute tests, its drag coefficient at Mach number 0.9 is higher than that of the wind tunnel test. This behavior has been observed in wind tunnel test data [35], and it is due to the interaction between the blunt aeroshell and the parachute flow fields.

The oscillation angle of the parachute within 7 s after the parachute inflation is shown in Figure 16. After the parachute inflation, the parachute shows repeated oscillation within a small angle. The oscillation angle of test 03 is the largest, about 20°, and the maximum oscillation angle of the other tests is 15°. Since the dynamic pressure in the flight tests is much smaller than that in the wind tunnel tests, the oscillation angle of the parachute is larger than that in the wind tunnel test results.

![Figure 14: Opening force versus time.](image)

![Figure 15: Drag coefficient versus Mach number.](image)

![Figure 16: Oscillation angle versus time.](image)

The test results show that between $Ma_{0.2}$ and $Ma_{2.4}$, the drag coefficient of the tapered DGB parachute increases first and then decreases. The variation range of the drag coefficient is 0.39~0.70. At $Ma_{1.5}$, the drag coefficient reaches the maximum value of about 0.7.

5. Conclusion

In this paper, the parachute of Tianwen-1 has been optimized and tested. According to the flight conditions of Mars parachutes, five DGB parachutes with different geometries were designed. In the wind tunnel tests, the change of drag coefficient and oscillation angle under different Mach numbers were obtained. Based on the comprehensive performance of the parachute, the tapered DGB parachute is selected as the priority parachute type. Then, the tapered DGB parachute was verified by four high-altitude flight tests using sounding rockets to reach the targeted conditions. The test results indicate that the drag coefficient of the tapered DGB parachute varied from 0.39 to 0.70 with the Mach number increased from $Ma_{0.2}$-$Ma_{2.4}$ and reached the maximum value of 0.7 at $Ma_{1.5}$; the maximum AOA after parachute deployment is about 20°, which have all demonstrated that the performance of the tapered DGB parachute could meet the deceleration requirements of the Tianwen-1 Mars probe.

Data Availability

The data used to support the findings of this study are available from the author upon request.
Conflicts of Interest
All authors declare no conflicts of interest.

Authors’ Contributions
All authors participated in the research design and conducted the experiments. Mingxing Huang performed data analysis and accomplished the writing of the manuscript.

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