Ejection Separation Characteristic Analysis of Parachute Container Cover from Return Capsule for Lunar Exploration

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Abstract: The parachute container cover ejection separation is the first and foremost motion for the return capsule recovery system, which is related to the success of a recovery system. Adopting the computational fluid dynamics (CFD) simulation and flight dynamics coupling method, the parachute container cover ejection separation is simulated. The rationality of the ejection separation speed and dynamic characteristics of the separation process is analyzed. Meanwhile, the influences of angle of attack, Mach number and ejection separation speed on the parachute container cover ejection are also investigated. Results show that the ejection separation speed design is reasonable. It has a certain design margin for parachute container cover to escape from the wake region, and to pull out the drag parachute completely. The results may provide a theoretical basis for recovery system engineering design of the lunar exploration project.

Key words: lunar sample return; recovery system; ejection separation; computational fluid dynamics (CFD)
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1 Introduction

The ejection separation of parachute container cover in a spacecraft recovery system is mainly to provide a parachute opening channel. Meanwhile, the kinetic energy of the ejected cover is also needed to lead a pilot parachute or to make the drogue chute straight[1-3]. The ejection separation of parachute container cover is the first key executive action for the recovery system. Once the control device of recovery program sends the order "Parachute container cover ejection" out, the cover device will be actuated and the parachute container cover with a certain initial relative separation velocity leaves from the return capsule. And then under the integrated action of respective inertia, gravity, and aerodynamic force, as well as the interaction of erodynamic interference, the parachute container cover detachs from the return capsule gradually, until the pilot parachute or the drag parachute is fully pulled out. It is a big concern in the design of recovery system whether the ejection separation process of the parachute container cover is normal or not[4-5]. In a normal process, the parachute container cover should quickly escape from the wake region of the return capsule, pull the parachute bag out and make the drag parachute straight.

Four catapult separator parachute container covers are to be employed in the design of the recovery system of China Lunar sample return. Due to overall layout requirement of the return capsule for the lunar sample return, the lateral parachute container cover ejection mode is adopted, which is similar to the cover ejection mode of Shen Zhou spacecraft with a stable wing. Its aerodynamic shape is irregular and its mass characteristics have less significance than those of manned spacecraft,

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which obviously affect the kinematic characteristics of the separation process of parachute container cover ejection. Besides, since the aerodynamic shape of the parachute container cover is complex, it is difficult to accurately obtain the aerodynamic parameters at the initial design stage. The parachute container cover separation in the wake region of return capsule and the separation speed of parachute container cover ejection can only be determined by estimation and experience. For reliability and safety, it is therefore necessary to carry out the research on the appropriate ejection velocity of separation parachute container cover as well as the influences of dynamic characteristics of conditions and factors on the parachute container cover ejection separation process.

In this paper, using computational fluid dynamics (CFD) code Fastran as the main computing platform, the dynamic characteristics of parachute container cover ejection separation process of the return capsule device for the lunar sample return are studied based on the method of coupling CFD numerical calculation and flight dynamics, i. e. CFD-6DOF method[6-12].

2 Analytical Method

Since the ejection duration time is very short, the distance between the parachute container cover and return capsule is short. The ejection separation process essentially belongs to unsteady flow field of two bodies under the action of complex physical separation, which can be considered as a process with tight coupling of fluid dynamics and flight dynamics . There exists mutual interference among objects. And with the relative configuration changes, aerodynamic behavior presents a non-linear characteristic.

The characteristics of parachute container cover ejection separation process are numerically investigated in this paper, using the overlapping grid (nested) numerical calculation of CFD technology and 6DOF flight dynamics coupling method. The main computing platform is the commercial software CFD-Fastran. The dynamic characteristics of the unsteady flow conditions and parachute container cover ejection separation process are analyzed.

To avoid complicated analysis, the following simplifications are taken. Since the change in motion cabin is unknown, changes of cabin velocity and attitude are neglected during simulations. Moreover, we mainly consider the aerodynamic force and gravity of the parachute container cover in a separation process, while omit other forces that seem to be least important.

The return capsule, the parachute container cover shape, and the assembly of them are shown in Figs. 1—3. In the calculation, the height of the return capsule ejection cover is 10 km, the speed angle −56°, and the sideslip angle 0°. Different combinations of Mach number, angle of attack, and ejection separation speed are considered in the simulations.

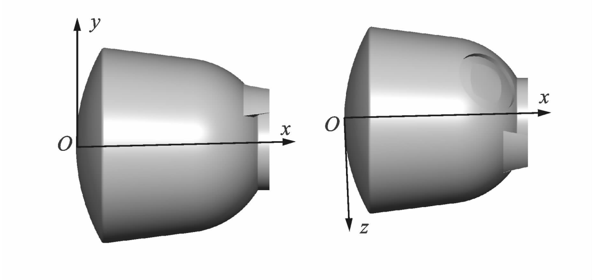


Fig. 1 Return capsule model

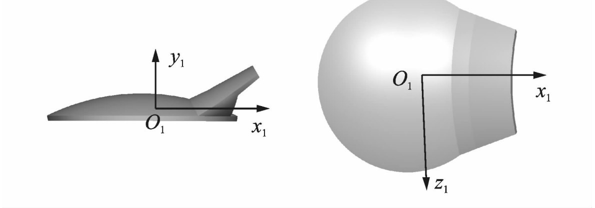


Fig. 2 Parachute container cover model

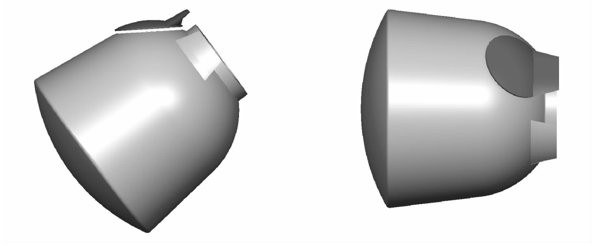


Fig. 3 Assembly of return capsule and parachute container cover

3 Analytical Model

The Euler equation in a conservative form holds

$$\frac{\partial Q}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}+\frac{\partial G}{\partial z}=0 \tag{1}$$

where Q is the conservation variables. E, F, G are the convection fluxes, and E_{v}, F_{v}, G_{v} the viscous fluxes.

$$Q=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho w\\ \rho e\end{bmatrix}\quad E=\begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ \rho uw\\ u(\rho e+p)\end{bmatrix}$$

$$F=\begin{bmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ \rho vw\\ v(\rho e+p)\end{bmatrix}\quad G=\begin{bmatrix}\rho w\\ \rho uw\\ \rho vw\\ \rho w^2+p\\ w(\rho e+p)\end{bmatrix}$$

where ρ is the gas density, u, v, w the x, y, z direction velocities, e the energy and p the pressure.

The rigid body dynamics equations in form of vector can be written as follows

$$\boldsymbol{F}=m\,\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} \tag{2}$$

$$\boldsymbol{M}=\frac{\partial \boldsymbol{h}}{\partial t}+\boldsymbol{\omega}\times\boldsymbol{h} \tag{3}$$

where $\boldsymbol{F}$, $\boldsymbol{M}$, m and $\boldsymbol{\omega}$ are the force, the torque, the mass and the rotational speed, respectively. The momentum $\boldsymbol{h}=\boldsymbol{I}\boldsymbol{\omega}$, here, $\boldsymbol{I}$ is the moment of inertia of the moving object.

In the 6DOF motion module, we need to solve six scalar equations, i. e. , to calculate the displacement and velocity of a rigid body from force and moment by a series of iterative steps. The calculation process can be expressed as follows:

(1) It is assumed that at the initial time t, velocity, rational velocity and moment vector of momentum are labelled as $\boldsymbol{v}^t$, $\boldsymbol{\omega}^t$ and $\boldsymbol{h}^t$, respectively.

(2) By means of CFD solver, the flow field characteristics can be obtained, and then $\boldsymbol{F}$ and $\boldsymbol{M}$ are calculated by considering aerodynamics and gravity, etc.

(3) The velocity and displacement can be obtained by linear iteration

$$v_x^{t+\Delta t}=v_x^t+\Delta t(F_x^{t+\Delta t}/m) \tag{4}$$

$$\delta x^{t+\Delta t}=(v_x^{t+\Delta t}+v_x^t)\,\frac{\Delta t}{2} \tag{5}$$

(4) Likewise, inertia moment, rational and angular velocities can be calculated by linear iteration

$$\boldsymbol{h}^{t+\Delta t}=\boldsymbol{h}^t+\Delta t(\boldsymbol{M}^{t+\Delta t}-\boldsymbol{\omega}^t\times\boldsymbol{h}^t) \tag{6}$$

$$\boldsymbol{\omega}^{t+\Delta t}=\boldsymbol{I}^{-1}\boldsymbol{h}^{t+\Delta t} \tag{7}$$

$$\delta\boldsymbol{\theta}^{t+\Delta t}=(\boldsymbol{\omega}^{t+\Delta t}+\boldsymbol{\omega}^t)\,\Delta t/2 \tag{8}$$

(5) After the aforementioned processes, displacements ($\delta x, \delta y, \delta z$) and rotations ($\delta\theta_x$, $\delta\theta_y$, $\delta\theta_z$) can be obtained and used for new positions.

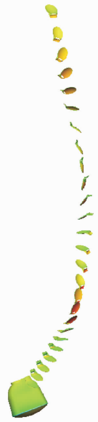
Since the chimera grid method possesses the advantages of relatively little calculation time and once-generated grids, it is utilized in this calculation. When generating the chimera grid, a main grid is modeled to contain the whole flow field, while a sub-structured grid only includes a specific object (bullet, parachute container cover for instance). The sub-structured grids are independent of the main grid and can move freely. Interpolation method is employed for the data transmission between the main and sub-structured girds. Consequently this method is suitable for a multi-body kinematical problem. The mesh partition of flow field is based on chimera grids method. The return becomes main grids, while the parachute container cover becomes sub-structured grids.

4 Results and Discussion

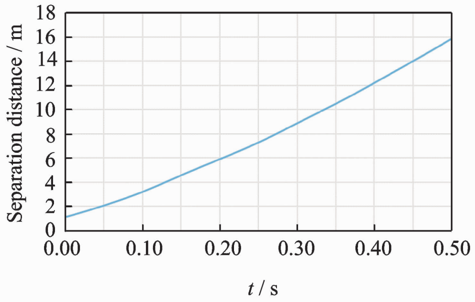
4.1 Calculation results at typical operating conditions

According to the preliminary design of recovery system for lunar exploration, the operating conditions of a normal return are defined as that the parachute container cover ejection separation is at the height of 10 km, the speed dip angle about −56°, Mach number about 0.35, the angle of attack about −13°, the sideslip angle about 0°, and the separation velocity of 22 m/s approximately. Numerical simulations are performed under the typical conditions listed above, and the results are shown in Fig. 4, where θ_x, θ_y, θ_z are the attitude angular of the parachute container cover, and Ω_x, Ω_y, Ω_z the attitude angular velocity, respectively.

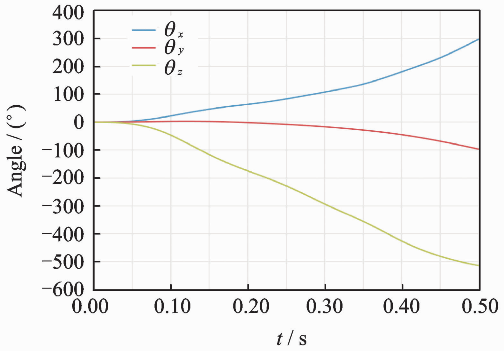
Without considering the effect of drag parachute's resistance on the ejection separation of the parachute container cover, the separation distance reaches 13 m in about 0.42 s. The result of a rocket sled test is about 0.45—0.6 s. It is obvious that the parachute pull-out resistance has some impact on the parachute container cover separation time. Simulation results show that the parachute container cover rolls a cycle. Moreover, the maximum component of angular velocity ω_Z is close to 1 500 °/s, and the other component ω_x approaches 1 500 °/s in 0.5 s.



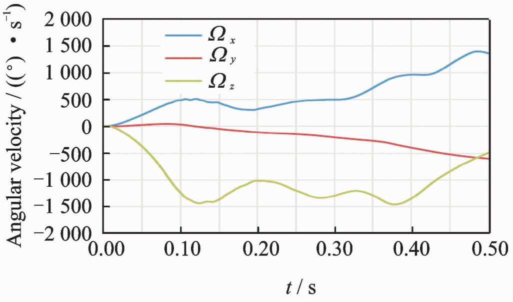
(a) Parachute container cover separation process



(b) Change of separation distance with time



(c) Change of angle with time



(d) Change of angular velocity with time

Fig. 4 Typical simulation results

The calculation results also indicate that the ejection separation speed of 22 m/s can make the parachute container cover leave the wake region of the return capsule and pull out the drag parachute completely. During the pulling-out, the rolling of the parachute container cover is improved. In the rocket sled test, the parachute container cover rolled less than a circle in the pulling-out process of the parachute. Therefore, the design ejection separation speed of the recovery system is considered as a reasonable and feasible one.

4.2 Influences of three main factors

4.2.1 Effect of angle of attack

To analyze the influence of angle of attack on the dynamic characteristics of the parachute container cover during the separation process, numerical simulations are performed at Mach number $Ma=0.5$ and ejection velocity $v=16$ m/s. Three angles of attack are considered, namely, −20°, 0° and −90°. The simulation results are shown in Figs. 5, 6. It can be seen that the angle of attack directly affects the flow field between return capsule and parachute container cover and its mutual interference, which has a strong influence on the motion trajectory and attitude of the parachute container cover. Although compared with the case of $\alpha=-90°$ the attitude of the parachute container cover changes acutely at $\alpha=0°$ and $\alpha=-20°$, the relative trajectories are reasonable. At $\alpha=-90°$, the separation trajectory cannot move along the direction of the ejection separation but "turn back", and the separation distance changes slowly due to the flow influence . The obvious slow change of separation distance is unfavor-

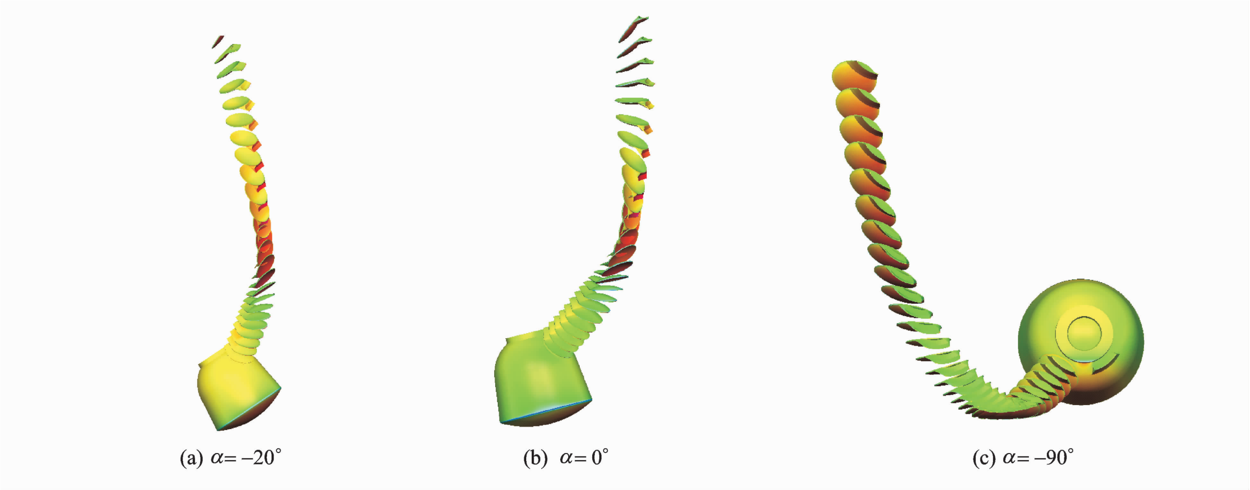
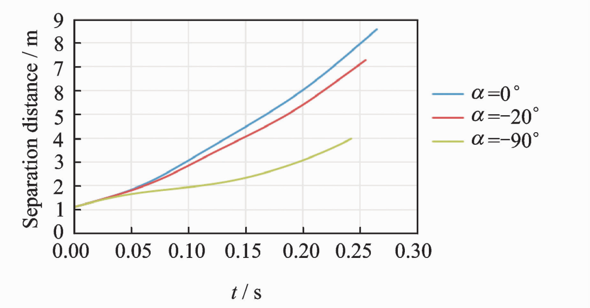
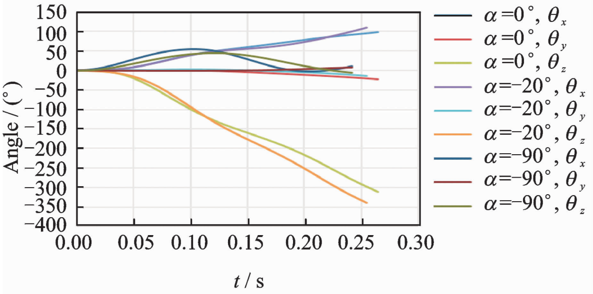

(a) $\alpha=-20^\circ$ (b) $\alpha=0^\circ$ (c) $\alpha=-90^\circ$

Fig. 5 Separation process of parachute container cover at different angles of attack



(a) Change of separation distance with time



(b) Change of angle with time

Fig. 6 Simulation results at different angles of attack

able to the pulling-out of the parachute. Therefore, this condition, $\alpha=-90^\circ$, should be avoided.

4.2.2 Effect of Mach number

To analyze the effect of Mach number on the dynamic characteristics of parachute container cover in the separation process, similar simulations are carried out at the angle of attack $\alpha=-20^\circ$ with ejection velocity $v=16$ m/s. Three Mach numbers 0.4, 0.5 and 0.7 are considered. The results are shown in Figs. 7,8, which suggest that at the same angle of attack and ejection velocity, Mach number can affect the trajectory and attitude change of the parachute container cover.

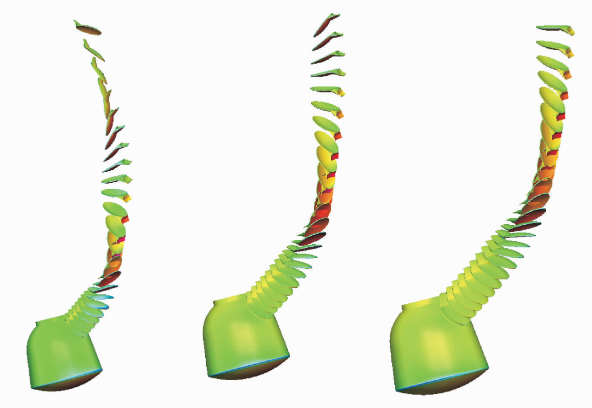
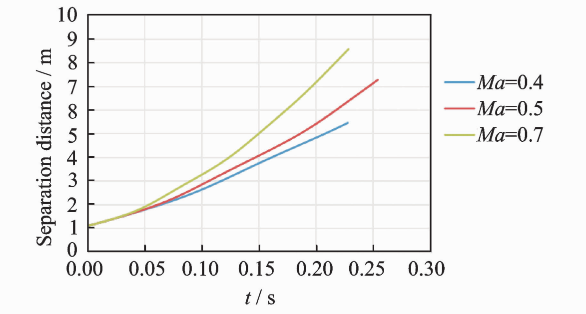

(a) Ma=0.7 (b) Ma=0.5 (c) Ma=0.4

Fig. 7 Separation process of parachute container cover at different Mach numbers

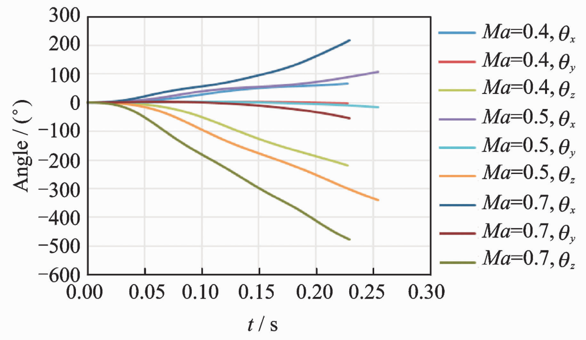
The larger the Mach number is, the farther the parachute container cover separates from the return capsule at the same moment. In addition, the larger the Mach number, the faster the attitude change, and the bigger the oscillation amplitude. It is because the motion trajectory and attitude of the parachute container cover are influenced more by the aerodynamic effect at the higher Mach number.

4.2.3 Effect of ejection speed

Numerical simulations are also conducted at $Ma=0.5$ and $\alpha=-20^\circ$ to analyze the influence of ejection speed on the dynamic characteristics of



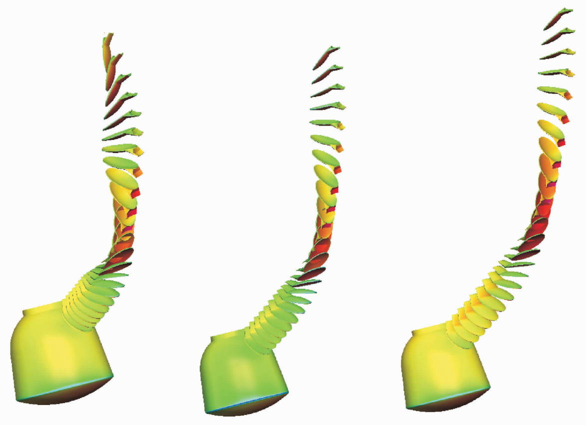
(a) Change of separation distance with time



(b) Change of angle with time

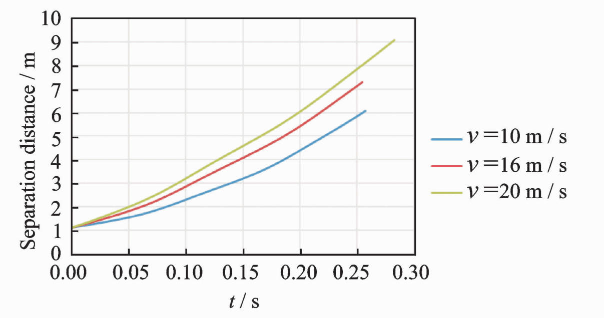
Fig. 8 Simulation results at different Mach numbers

cover ejection. Three ejection speeds 10 m/s, 16 m/s and 20 m/s are included. The results are shown in Figs. 9,10. It can be seen that at a fixed Mach number and angle of attack, the larger the ejection speed is, the farther the parachute container cover is away from the return capsule, the better the ejection separation is, and the stronger the ability of the separation process is to against unfavorable conditions of flow angle of attack. Besides, among the three ejection speeds, the 22 m/s one has the largest design margin.

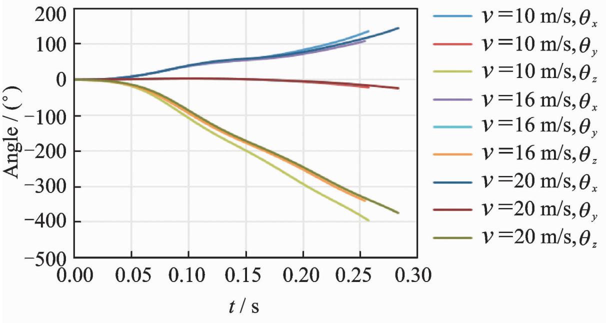


(a) v=10 m/s (b) v=16 m/s (c) v=20 m/s

Fig. 9 Separation process of parachute container cover at different ejection speeds



(a) Change of separation distance with time



(b) Change of angle with time

Fig. 10 Simulation results at different ejection speeds

5 Conclusions

Based on the comparative analysis of different angles of attack, Mach numbers, and ejection speeds, the following conclusions can be drawn:

(1) Under the normal return conditions, the separation distance can reach about 14 m in about 0.45 s after ejecting the cover. That is to say, with the ejection speed of 22 m/s the parachute container cover can be outside the wake region of the return capsule and the parachute is fully pulled out. A design margin is achieved and the design of the recovery system for lunar sample return can thus be regarded as feasible.

(2) Angle of attack has the most significant effect on the dynamic characteristics of parachute container cover separation process. The angle of attack $\alpha=-90°$ should be avoided, at which the separation trajectory displays a ″turn back″ phenomenon. The angles of attack $\alpha=-20°$ and $\alpha=0°$ can ensure the reliability and safety of the cover separation process.

(3) Increasing the ejection speed is helpful to

resist various kinds of unfavorable interference during the ejection and separation process of the parachute container cover.

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