Research Article

Flight Trajectory Simulation and Aerodynamic Parameter Identification of Large-Scale Parachute

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In this paper, the multibody parachute-payload system is simplified and analyzed. A six-degree-of-freedom rigid body flight dynamic model is established to calculate the flight trajectory, attitude, velocity, and drop point of the parachute-payload system. Secondly, the random interference factors that may be encountered in the actual airdrop test of the parachute system are analyzed. According to the distribution law of the interference factors, they are introduced into the flight dynamic model. The Monte Carlo method is used to simulate the target and predict the flight trajectory and landing point distribution of the parachute system. The simulation results can provide technical support and theoretical basis for the parachute airdrop test. Finally, the genetic algorithm is used to identify the aerodynamic parameters of the large-scale Disk-Gap-Band parachute. The simulation results are in good agreement with the test results, which shows that the research method proposed in this paper can be applied to study practical engineering problems.

1. Introduction

Because of its high deceleration efficiency and reliability, a parachute is an important decelerator in the recovery system [1], which is widely used in spacecraft return, Mars probe landing, and other missions [2]. Flexible parachutes are vulnerable to the complex and varied external environment during the recovery process. Therefore, it is necessary to thoroughly study the performance of the parachute system under various possible conditions in order to ensure the high reliability and high safety requirements of the aerospace engineering tasks [3].

Common methods for studying the performance of parachute systems include wind tunnel test, airdrop test, and computer simulation [4]. There are many limitations in wind tunnel test methods, which are mainly manifested in the small size of the wind tunnel, the high pressure, and the density of the test airflow. The parachute with scale model cannot guarantee the similarity of geometry and stiffness for a real parachute system. Therefore, accurate parachute parameters required for engineering development cannot be obtained by wind tunnel testing alone. Airdrop test methods can obtain some parachute performance parameters more accurately. However, their shortcomings are high test cost, long cycle, and limited numbers of tests, and they are subject to meteorological conditions. So, it is difficult to examine the characteristics of the system under various extreme conditions. Moreover, the installation difficulty of the measuring equipment makes it impossible to measure some important parachute system parameters. The working process of the parachute system is greatly affected by random environmental factors. It is difficult to comprehensively evaluate the performance of the parachute system only through test methods. However, the simulation method can make up for the deficiencies of the experimental methods. It is of great significance for improving the design level, reducing the numbers of tests, shortening the development cycle, saving design cost, and ensuring the safety of airdrop [5].

In this paper, a general trajectory simulation model of the parachute system airdrop test with random interference factors is established, and various deviation factors that may occur in the actual test are analyzed. A sufficient number of simulation target practices with the Monte Carlo method were carried out to check the strength of the parachute and
to verify the accuracy and dispersion of the random fall points. Therefore, it can provide experimental gist for improving the precision of airdrop, reducing the dispersion of the fall point, and correcting flight trajectory. On the other hand, measurable information for large parachutes is scarce, and their aerodynamic coefficients are difficult to obtain. Therefore, based on the actual airdrop test, the genetic algorithm is used to identify the aerodynamic parameters of large-scale Disk-Gap-Band parachute. This identification method can be used to study practical problems in engineering.

2. Modeling

2.1. Parachute-Payload System Dynamic Model. Before establishing a six-degree-of-freedom trajectory model of the parachute-payload system, the following assumptions are made:

The parachute-payload system is composed of parachute and payload body which are rigidly connected. The aerodynamic force of the parachute is at the geometric center of the parachute canopy. The drag area of the main parachute and payload body which are rigidly connected. The aerodynamic force of the parachute is at the geometric center of the parachute canopy. The drag area of the main parachute increases with time and is a function of time [6]. Ignoring the inflation process of the guide parachute, only the aerodynamic parameter identification of the test parachute is considered.

Figure 1 is a schematic diagram of a parachute-payload system, in which the parachute body coordinate system and the geodetic coordinate system are defined. The parachute coordinate system is oxyz, where the origin o is the geometric center of the parachute canopy, namely, the aerodynamic pressure center of the parachute. Point C is the center of mass of the parachute-payload system, and the distance from coordinate origin o to point C is Xg. The origin O_d of the geodetic coordinate system coincides with the projection point of the center of mass of the projectile at the initial time on the local horizontal plane. The O_dX_d and O_dY_d axes are in the local horizontal plane, pointing north and east, respectively.

2.2. Dynamic Equation. Using the Lagrangian method, the basic equations of motion of the parachute-payload system can be obtained. The general form is as follows: 

\[
\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{V}} \right) + \Omega \times \left( \frac{\partial T}{\partial \dot{V}} \right) = F, \tag{1}
\]

\[
\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{\Omega}} \right) + \Omega \times \left( \frac{\partial T}{\partial \dot{\Omega}} \right) + V \times \left( \frac{\partial T}{\partial V} \right) = M. \tag{2}
\]

The above formulas are also known as the Kirchhoff equation, where T is the kinetic energy of the system, F and M are the external forces and moments acting on the parachute system, respectively, and V and Ω, respectively, are the system velocity and the angular velocity vector. In the body coordinate system of the parachute system, formulas (1) and (2) are composed of the following forms, where \(v_x, v_y, v_z\) and \(\omega_x, \omega_y, \omega_z\) are the components of the velocity and angular velocity of the parachute system on each axis of its body coordinate system, respectively, \([I_{xx}, I_{yy}, I_{zz}]\) is the rotational inertia of the parachute system on each axis, and \(m\) is the total mass of the system.

\[
F = \begin{bmatrix}
(m + a_{11}) v_x - (m + a_{33}) (v_y \omega_z - v_z \omega_y) - (mx_g + a_{26}) \left( \omega_y^2 + \omega_z^2 \right) \\
(m + a_{33}) (v_y - v_z \omega_x) + (m + a_{11}) v_y \omega_x + (mx_g + a_{26}) (\omega_z + \omega_y \omega_x) \\
(m + a_{33}) (v_z + v_y \omega_x) - (m + a_{11}) v_y \omega_y - (mx_g + a_{26}) (\omega_y - \omega_z \omega_x)
\end{bmatrix}
\]

\[
M = \begin{bmatrix}
I_{xx} \omega_x + (I_{xx} - I_{zz} - a_{66}) \omega_z \omega_x - (mx_g + a_{26}) \left( v_z - v_y \omega_x + v_z \omega_y \right) + (a_{11} - a_{33}) v_y v_z \\
(I_{zz} + a_{66}) \omega_z + (I_{xx} - I_{zz} - a_{66}) \omega_y \omega_x - (mx_g + a_{26}) \left( v_z + v_x \omega_y - v_z \omega_x \right) - (a_{11} - a_{33}) v_y v_z
\end{bmatrix}
\]
3. Method

3.1. Fall Point Prediction Method

3.1.1. Trajectory Deviation Factor. The parachute system is susceptible to various random environmental factors during its operation, which results in some state parameters of the system deviation greatly from the design state. The extreme conditions caused by these deviations can maximize the peak opening force and dynamic pressure. Peak opening force is one of the important indexes to ensure the safety and reliability of the parachute system. It directly affects whether the parachute system can be opened normally or not and is related to the success or failure of the whole recovery mission [7].

Because the airdrop process includes many stages and involves many influencing factors, it is necessary to establish a multistage simulation model for analysis [8]. According to the airdrop test procedure, the airdrop process is simplified to several stages as shown in Figure 2.

Due to the influence of various random factors, various deviations may occur in the design parameters of the system. These deviations will cause the deviation of trajectory, thus affecting the landing position of the projectile. The disturbance factors include initial condition deviation, experimental model deviation, control parameter deviation, parachute drag area deviation, and wind influence. The deviation of initial conditions is composed of throwing speed and height error. Experimental model deviations include mass, inertia, and centroid bias. Control time and dynamic pressure errors are contained in the parachute control condition deviation. Parachute drag area deviation involves the drag area deviation of the guided parachute, test parachute, reeﬁng main parachute, and full inflation main parachute. For random wind, it is assumed that the wind speed obeys normal distribution and the wind direction is uniformly distributed in the horizontal plane. Each interference factor in the simulation is a random variable that follows a normal distribution. Therefore, the standard normal distribution function randn can be used to obtain random variable samples with normal distribution in simulation.

3.1.2. Monte Carlo Method. Because of the large number of interference models involved, it is difficult to directly obtain the influence of the variation factors on the trajectory within their deviation range by the analytical method.

Using the Monte Carlo method, the target test can be simulated many times by computer simulation. Each simulated target is considered as an actual airdrop test. The results with good convergence can be obtained by the simulation method, which provides a basis for the formulation of a test scheme and system design.

The Monte Carlo method, also known as a random simulation method or random sampling method, is a classical statistical test method. Its basic theory is the law of large numbers and the central limit theorem [9]. According to the law of large numbers, the accuracy of the evaluation improves as the number of simulations increases [10, 11]. In parachute airdrop test trajectory simulation, it is usually necessary to determine the standard values and deviations of each random factor and then use the random number generator to generate the corresponding pseudorandom number sequence. Then, it is substituted into the established parachute system dynamic model for calculation. Finally, by statistical processing of the calculated results, the relatively accurate simulation results of disturbed trajectory and landing point prediction can be obtained. Using the Monte Carlo method to simulate target, the following steps can be taken [9]:

1. Analyzing the dynamic characteristics of the parachute-payload system and establishing the trajectory simulation mathematical model of the parachute system

2. Determining all kinds of random deviations and random interference factors in the process of an airdrop. The pseudorandom number sequence of each random variable is generated according to the distribution type and statistical characteristics of random factors

3. The Monte Carlo method is realized by using MATLAB programming. The sampling values of random variables are substituted into the dynamic
Figure 3: Three-dimensional trajectory curve.

Figure 4: Longitudinal plane trajectory curve.

Figure 5: Speed-time diagram.
model of the parachute system. A trajectory curve and a landing coordinate can be obtained by running the program once.

(4) According to the required number of tests, the program is cyclically run \( n \) times so as to obtain sampling simulation of random trajectory parameters, that is, simulated target.

(5) The simulation results are statistically processed, and the mean and variance of the distance between each fall point and the ideal undisturbed landing point are calculated to evaluate the scattering of the falling point.

3.2. Parameter Identification Method. Dynamic parameter identification is essentially a complex nonlinear constraint optimization problem. If the traditional optimization algorithm is used to solve, it will involve a series of problems, such as the gradient calculation of the function and the selection of the initial value of the iteration. In addition, the large-scale Disk-Gap-Band parachute used for Mars exploration has almost no measurable data, and its explicit identification equation is difficult to establish. As a nondeterministic quasi-natural algorithm, a genetic algorithm is an effective method to solve such optimization problems. It is a global heuristic optimization algorithm with adaptive probability search and low sensitivity to initial values. Because of its advantages such as simplicity, easy operation, and strong robustness, it has been widely used in aerodynamic parameter identification of various aircraft. In this paper, it is applied to the identification of the aerodynamic parameters of the large-scale Disk-Gap-Band parachute, which solves the problem that the aerodynamic force of the parachute is difficult to calculate.

The genetic algorithm is an iterative algorithm. It has a set of solutions at each iteration. This set of solutions is initially randomly generated. At each iteration, a new set of solutions is generated by genetic operations that simulate evolution and inheritance. Each solution is evaluated by an objective function, and one iteration becomes a generation. Typical algorithm steps are as follows:

1. Initialize the population
2. Calculate the fitness of each individual in the population
3. Select individuals who will enter the next generation according to a certain rule determined by the individual fitness value
4. Cross operation according to probability \( p_c \)
5. Perform mutation operation according to probability \( p_m \)
6. If some stopping conditions are not met, go to (2), otherwise, go to the next step.
Output the chromosome with the best fitness in the population as a satisfactory or optimal solution to the problem

4. Simulation Results

4.1. Fall Point Prediction Results

4.1.1. Ideal Trajectory. In this paper, the airdrop test of a projectile with Disk-Gap-Band parachute is taken as an example to simulate. The projectile is a cone-shaped head with a central cylindrical section and a cross-shaped wing at the tail. The aerodynamic data are obtained by CFD numerical simulation [12]. Given each characteristic parameter and a set of standard launching conditions, the disturbance factors are set to zero to simulate, and the states of the parachute are calculated (or obtained) by solving the differential equations of motion. The ideal trajectory curve of the parachute-payload system and the relationship between the velocity, height, pitching angle, and trajectory inclination with time are obtained, as shown in the following figures.

As can be seen from Figures 3 and 4, the deviation of the ideal windless trajectory in the lateral distance (Z direction) is very small and can be neglected, so it can be considered as a two-dimensional trajectory in the longitudinal symmetry plane. Figures 5 and 6 are graphs of the speed and height changes with time during descent, respectively. From the pitch angle curve (Figure 7), it can be seen that the pitch
attitude of the projectile changes more dramatically when the parachute is full, because the effect of the parachute on the projectile is equivalent to applying a drag on the projectile’s tail, thereby increasing the pitch moment of the projectile. The parachute opening process has a great influence on the attitude change of the projectile; but with the parachute opening, the influence decreases gradually. Throughout the process, the pitching attitudes of the projectile change from horizontal to near to vertical direction as shown in Figure 8.

4.1.2. Disturbed Trajectory. The random disturbance value of each deviation factor is added to the ideal trajectory for simulation. The simulation result of each trajectory is equivalent to the actual trajectory of the airdrop test. After 1000
simulations were repeated, the scattering map of the fall points is obtained as shown in Figure 9. The horizontal and vertical coordinates of each fall point are statistically compared with the ideal fall point to get the scattering rule of the fall point. As can be seen from the figure, the maximum vertical scattering does not exceed 3000 meters, and the maximum lateral scattering does not exceed 400 meters. The simulation trajectory landing points are evenly distributed around the ideal trajectory landing point.

The estimated value of the circular error probability (CEP) after 1000 simulated targets was calculated as $\text{CEP} = 779.0536$ m.

The longitudinal ($x$-axis) position circular error probability of the simulated fall points is $\text{CEP} = 794.5499$ m. The mean value of the longitudinal deviation $\Delta x$ between the simulated trajectory landing points and the ideal landing point is 300 m, and the mean square error is 1084 m. The normal distribution of the longitudinal coordinates $X$ of the falling
points is tested, and the results are shown in Figure 10. It can be seen that the longitudinal positions of the falling points conform to the normal distribution well.

The lateral ($z$-axis) position circular error probability of the simulated fall points is $\text{CEP} = 115.2857$ m. The mean value of the lateral deviation $\Delta z$ between the simulated trajectory landing points and the ideal landing point is 3 m, and the mean square error is 153 m. The normal distribution of the lateral coordinates $Z$ of the falling points is tested, and the results are shown in Figure 11. It can be seen that the lateral positions of the falling points conform to the normal distribution well.

Calculating the deviation between the falling points of each simulation and the ideal falling point and plot the falling-point deviations of 1000 simulations on the same picture are plotted as shown in Figure 12.

It can be seen from Figure 12 that the distance deviations between the simulated falling points and the ideal falling point are mainly concentrated within 500 meters, the maximum deviation is about 2000 meters, the average value of the distances is 892.5002 m, and the standard deviation is 641.1984 m. The normality test is performed on the falling-point deviations, as shown in Figure 13, and it can be seen that the deviations of the landing points are in good agreement with the normal distribution law.

As mentioned above, the ejection condition of the test parachute is that the dynamic pressure reaches a fixed value,
and the flight angle of attack of the parachute system affects the measurement of the dynamic pressure by the pitot tube. Therefore, it is necessary to check the distribution of the flight angle of attack of the parachute system when it reaches the dynamic pressure of the ejection. Figure 14 is the angle of attack distribution histogram when dynamic pressure is 750 Pa measured by the pitot tube.

It can be seen from the figure that in about 90% of 1000 simulations, the angle of attack at the time of the test parachute ejection is less than 20°. In rare cases, the angle of attack is even greater than 80°. If the angle of attack is too large, the pitot tube measurement may not be accurate, so the parachute-payload system model needs to be further improved.

### 4.2. Parameter Identification Results

The aerodynamic parameter identification of parachute is to estimate the aerodynamic coefficient of the parachute by establishing the system mathematical model based on the test data obtained from the airdrop test. In this paper, based on the above dynamic model, the parameters of test parachute are identified by stages based on a genetic algorithm [13].

#### 4.2.1. Steady Descent Stage

During the steady descent stage, the test parachute is fully opened. For simplicity, assuming that its drag coefficient is a constant, written as

\[ C_T = \text{const} = p(1), \]  

where \(C_T\) is the drag coefficient and \(p(1)\) is the parameter to be identified. The initial parameters of the genetic algorithm are set as follows: the population size is 100, the generation number is 100, the crossover probability is 0.7, and the mutation probability is 0.001. Taking the \(Y\)-direction velocity as the observation measurement, the identification result is

\[ C_T = p(1) = 0.7616. \]

The identification result is substituted into the program for simulation, and comparing it with the test data, as shown in Figure 15.

It can be seen from Figure 15 that the simulation results in a steady descent stage are basically consistent with the test data, which can verify that the identification model is accurate.
4.2.2. Test Parachute Inflation Stage. During inflation, the aerodynamic coefficient of the test parachute is expressed as static aerodynamic coefficient multiplied by an inflation factor $K_I$, which is written as\[ K_I = p(2) \left( \frac{t - t_{LS}}{t_{FI} - t_{LS}} \right)^{p(3)} \] where $t_{LS}$ is the moment of rope straightening, $t_{FI}$ is the moment of full inflation, and $p(2)$ and $p(3)$ are the parameters to be identified. Taking the pull of rear cabin as the observation measurement, the identification result is $p(2) = 1.191$, $p(3) = 4.393$.

In the formula, $t_{LS}$ is the moment of rope straightening, $t_{FI}$ is the moment of full inflation, and $p(2)$ and $p(3)$ are the parameters to be identified. Taking the pull of rear cabin as the observation measurement, the identification result is $p(2) = 1.191$, $p(3) = 4.393$.

In the formula, $t_{LS}$ is the moment of rope straightening, $t_{FI}$ is the moment of full inflation, and $p(2)$ and $p(3)$ are the parameters to be identified. Taking the pull of rear cabin as the observation measurement, the identification result is $p(2) = 1.191$, $p(3) = 4.393$.

The identification result is substituted into the program for simulation, and comparing it with the test data, as shown in Figure 16.

It can be seen from Figure 16 that the simulation results of aerodynamic force in the inflation stage are basically consistent with the test, which proves that the identified inflation factor has a reference value.

4.2.3. Unloading Stage. During the unloading stage, the projectile nose suddenly separated from the rear cabin, and the load weight of the test parachute decreased momentarily, which caused the drag coefficient of the test parachute to suddenly decrease and then gradually recover. The aerodynamic coefficient in this process is expressed as the static aerodynamic coefficient multiplied by an unloading factor $K_{off}$ and written as

\[ K_{off} = 1 - (1 - p(4)) e^{-(t - t_{sep})/p(5)} \]

where $t_{sep}$ is the separation time and $p(4)$ and $p(5)$ are the parameters to be identified. Taking the pull of rear cabin as the observation measurement, the identification result is $p(4) = 0.747$, $p(5) = 1.093$.

The identification result is substituted into the program for simulation, and comparing it with the test data, as shown in Figure 17.

It can be seen from Figure 17 that the unloading stage lasted for about 2 seconds, and the simulation results of the pull are basically consistent with the test data.

The five parameters identified above were used to simulate the entire process of the test parachute from ejection to unloading, and compared with the test data, the results are as shown in Figures 18 and 19.

As can be seen from Figures 18 and 19, the simulation results agree well with the experimental data, which verifies the accuracy of the identification results.

5. Conclusion

(1) Based on the simplified analysis of the multibody parachute-payload system, a six-degree-of-freedom rigid body flight dynamic model and a landing-point calculation model are established. These models can satisfy the requirements of solving the trajectory, attitude, velocity, and landing-point dispersion of the multibody parachute-payload system. 

Figure 18: Height-time diagram.
Aerodynamic data of the parachute-payload system are obtained by CFD numerical simulation. Random interference factors of the parachute-payload system in an airdrop test are synthetically analyzed. Based on the MATLAB simulation tool and Monte Carlo method, a method of flight trajectory simulation and model construction under interference effect is proposed, which can effectively solve the dispersion of landing point under effects of various deviation factors.

The numerical simulation method of parachute-payload system flight trajectory proposed in this paper can provide simulation means for the research and verification of parachute-payload system flight trajectory and precise landing at expected points. It also has reference significance for general parachute airborne technology and multibody parachute system simulation.

A method for identifying aerodynamic coefficients of large Disk-Gap-Band parachute based on a genetic algorithm is proposed. This method can estimate the aerodynamic parameters of the parachute based on the airdrop test data and solves the problem that the aerodynamic force of the parachute is difficult to calculate. This identification model can solve the complex problem of fluid-structure coupling calculation and can be used in engineering practice.

### Nomenclature

- $T$: Kinetic energy
- $F$: External forces
- $M$: External moments
- $x, y, z$: Components of the position
- $v_x, v_y, v_z$: Components of the velocity
- $\omega_x, \omega_y, \omega_z$: Components of the angular velocity
- $I_{xx}, I_{yy}, I_{zz}$: Rotational inertia
- $\alpha$: Additional mass
- $m$: Total mass
- CEP: Circular error probability.

### Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

### Conflicts of Interest

The authors declare no conflict of interest.

### References

[1] A. Sengupta, A. Steltzner, and J. R. Al Witkowski, “An overview of the Mars Science Laboratory parachute decelerator system,” in *2007 IEEE Aerospace Conference*, Big Sky, MT, USA, 2007.

[2] J. R. Cruz, D. Way, J. Shidner et al., “Parachute models used in the Mars Science Laboratory entry, descent, and landing simulation,” in *AIAA Aerodynamic Decelerator Systems (ADS) Conference*, Daytona Beach, Florida, March 2013.

[3] J. M. Ginn, I. G. Clark, and R. D. Braun, “Parachute dynamic stability and the effects of apparent inertia,” in *AIAA Atmospheric Flight Mechanics Conference*, Atlanta, GA, June 2014.

[4] A. P. Taylor and E. Murphy, “The DCLDYN parachute inflation and trajectory analysis tool – an overview,” in *18th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar*, Munich, Germany, 2005.
[5] J. Moore and A. Morris, “Development of Monte Carlo capability for Orion parachute simulations,” in 21st AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, Dublin, Ireland, May 2011.

[6] G. Shen, Y. Xia, and H. Sun, “A 6DOF mathematical model of parachute in Mars EDL,” Advances in Space Research, vol. 55, no. 7, pp. 1823–1831, 2015.

[7] S. Torrers, “Determination and ranking of trajectory accuracy factors,” in 29th Digital Avionics Systems Conference, Salt Lake City, UT, USA, October 2010.

[8] M. Mcquilling, J. Potvin, and J. Riley, “Simulating the flows about cargo containers used during parachute airdrop operations,” in 28th AIAA Applied Aerodynamics Conference, Chicago, Illinois, July 2010.

[9] G. S. Fishman, “Monte Carlo. Concepts, algorithms, and applications,” Technometrics, vol. 39, no. 3, pp. 338–338, 1996.

[10] A. M. Ferrenberg and R. H. Swendsen, “Optimized Monte Carlo data analysis,” Physical Review Letters, vol. 63, no. 12, pp. 1195–1198, 1989.

[11] T. Hesterberg, “Monte Carlo strategies in scientific computing,” Technometrics, vol. 44, no. 4, pp. 403–404, 2009.

[12] H. Wong, J. Muylaert, D. Northey, and D. Riley, Assessment on EXPERT descent and landing system aerodynamics, ESA-SP 659, 2009.

[13] T. A. Talay, Parachute-deployment-parameter identification based on an analytical simulation of Viking BLDT AV-4, NASA TN D-7678, 1974.

[14] A. Witkowski, M. Kandis, and D. Adams, “Inflation characteristics of the MSL disk gap band parachute,” in 20th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, Seattle, Washington, 2009.