# Study on Influencing Factors of Parafoil Maximum Opening Force

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**Abstract:** In order to explore the opening force variation rules and influencing factors of parafoil opening process, a dynamic model for parafoil opening process is established in this paper. The performance of the parafoil opening process is calculated using the Runge-Kutta method. The calculation results are consistent with the patterns of the existing literatures, showing a maximum opening force error of 4.8%. Based on this, simulations are conducted for 20 different operating conditions of the parafoil system, and the rules governing the changes in system motion speed and parafoil opening force are obtained. The influence of the parafoil parameters and opening conditions on the opening force is also investigated. The results indicate that the opening force is positively correlated with the load mass, the opening speed, and trajectory angle, while it is negatively correlated with the opening height. The peak time of the opening force is affected by aerodynamic force and decelerating inertia force. As the weight and the opening height increase, the system deceleration becomes slower, and the peak time of the opening force is delayed. The aerodynamic force increases with the canopy area and the opening speed, leading to an advancement in the peak time of the opening force. Finally, the Sobol global sensitivity analysis method is employed to obtain the first-order sensitivity and total sensitivity coefficients of the parafoil parameters and opening conditions on parafoil maximum opening force. The results show that the opening speed and the load mass significantly affect the maximum opening force. The first-order sensitivity coefficients of 0.410 7 and 0.313 6, respectively; and the total sensitivity coefficients of 0.477 5 and 0.375 2, respectively. The sensitivity of the canopy area is at a moderate level, with the first-order and total sensitivity coefficients of 0.074 9 and 0.085 1, respectively. The sensitivity coefficients for the opening height and the opening angle are close to zero, indicating that fluctuations in their values have little effect on the maximum opening force.

**Key words:** parafoil; opening force; dynamics; Sobol method; sensitivity analysis

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## 0 Introduction

The parafoil's[1-2] unique structure allows it to open much faster than traditional parachutes. However, this rapid opening generates a large force, which can damage the fabric. As a core index for measuring the performance of parafoils, the opening force has become a focus for designers. However, as shown in Fig.1, since the parafoil is a structure with multiple airfoil chambers, the opening process involves the expansion of the airfoil and the aeration of air chamber. The structure shape and physical mechanism of parafoil opening process are far more complicated than those of ordinary parachutes. At present, the research results on parafoil opening performance are significantly lower than those of circular parachutes.

Historically, parafoil opening force data has relied on airdrop tests[3-4]. These tests are resource-intensive and can be influenced by factors

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Fig.1 Opening process of parafoil system

such as the airdrop platform and meteorological conditions. The theoretical numerical calculation is more suitable for mechanism analysis due to the large amount of data and controllable calculation conditions. In order to obtain performance data for the opening process more accurately, it is essential to carry out theoretical research on parafoil opening performance.

Due to the complex physical mechanism and the difficulty of coupling calculation, there are only a few exploratory studies on fluid-structure coupling of parafoil. Fogell et al.[5] used loose coupled fluid-structure interation (FSI) method to study the single chamber of parafoil during the opening and the steady shape with flow distribution was obtained. Nie et al.[6] proposed a coupled iterative approach based on the Robin-Neumann transmission condition to study the flow and structure change during the parafoil opening. The simulation results confirmed the two-stage changes in chordwise and spanwise. Liu[7] built an accordion-shape folded model for parafoils, and investigated the opening process under different flow conditions based on the arbitrary Lagrange Euler method. Consistent opening force and canopy shape with flight tests were obtained, and the effect of flow was discussed. Besides, Liu also examined the effect of reefing on the parafoil opening performance, and analyzed the mechanism of different reefing methods. Zhang et al.[8] further obtained the transient shapes of each chamber and parafoil aerodynamic characteristics with similar method. Miao[9] established a parafoil spanwise folding model with the sliding cloth closing control based on the S-ALE fluid-structure coupling method, and simulated and analyzed the influence of sliding cloth closing control on parafoil opening performance. In these research above, the parafoil opening process can be obtained accurately from the structural information, however, the computation cost of coupling is large with typical CPU time of 600 h.

In the flight dynamics method, the effect of the parafoil structure on its aerodynamics is estimated through theory and experiments, therefore the parafoil trajectories can be calculated with much lower computational costs. For instance, Garrard et al.[10] proposed a method to solve the particle motion equations. This involved measuring the lift and drag characteristics from experimental data over time. Potvin et al.[11] developed a theoretical model for the slider during the parafoil opening to obtain the transient aerodynamic characteristics, and the model was validated through comparison with experiments. Potvin et al.[12] further proposed a semi-empirical model to solve the opening force based on the momentum integral method and verified the model effectiveness through comparison with multiple tests results. Though this method, the correlations between the maximum opening force and opening conditions were obtained and the method was also successfully applied in group parachutes[13], fixed point airdrop[14], and NASA Orion main parachute[15]. Cheng et al.[16] established a two-body 9 DOF model of the parafoil system, conducted a study on the effects of hierarchical control and control speed on parachuting performance, and obtained the variation rules for the minimum horizontal speed, minimum vertical speed, and maximum attack angle of the parafoil. Li et al.[17] proposed a two-dimensional flight dynamics model for parafoil opening based on experimental measurements and obtained the opening force and motion trajectory which are consistent with flight tests results.

In this paper, flight dynamics model of ram-air parafoils is developed to investigate the effect of the parafoil parameters and the opening conditions on the opening force of parafoils. The global sensitivity analysis method of Sobol is introduced for the first time to quantitatively analyze the degree of influence of multiple parameters on the parafoil maximum opening force, and the multi-factor influence rule of the parafoil maximum opening force is obtained. The research results provide certain theoretical support for improving the reliability of the parafoil system.

# 1 Flight Dynamics Model of Parafoil Opening

## 1.1 Equations of parafoil motion

To simulate the flight of the airdrop system, the parafoil and load are simplified as a two-body system whose relative position remains constant and whose mass is concentrated at the system's center of mass. The effect of wind is not considered, and the system's motion is confined to the central plane of the system. The parafoil opening process is simplified into an initial inflation section and a filling section. In the initial inflation section, the air chambers are not yet inflated. At this point, the parafoil inflation resembles that of a square parachute, and the aerodynamic lift can be neglected. During the filling section, the canopy tilts forward, and the air chambers begin to inflate. The drag coefficient gradually decreases, while the lift coefficient gradually increases. This continues until the canopy is fully inflated.

As shown in Fig.2, the motion of the system is determined by the gravity, inertial forces and the aerodynamic force.

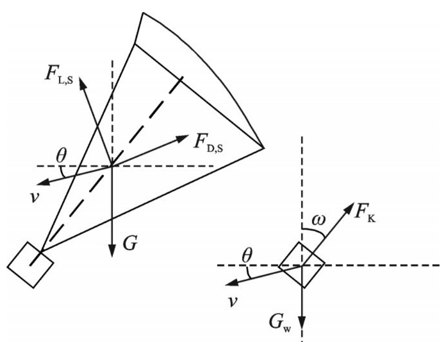



Fig.2 Inflation process diagram of parafoil

The equation of motion can be then expressed as

$$\begin{cases} (m_s+m_w)\dfrac{dv}{dt}= \\ (m_s+m_w)g\sin\theta-\dfrac{1}{2}\rho v_s^2(CA)_{D,s} \\ (m_s+m_w)v\dfrac{d\theta}{dt}= \\ \dfrac{1}{2}\rho v_s^2(CA)_{L,s}-(m_s+m_w)g\cos\theta \end{cases} \tag{1}$$

The opening force can be calculated by the following formula

$$\begin{cases} m_w\dfrac{dv}{dt}\cos\theta=F_K\cos\omega \\ m_w\dfrac{dv}{dt}\sin\theta=m_w g-F_K\sin\omega \end{cases} \tag{2}$$

where $m$, $v$, $g$, $\rho$, $\theta$, $\omega$ represent the load mass, velocity, gravitational acceleration, atmospheric density, trajectory angle, and pitching attitude angle, respectively; $(CA)_D$ and $(CA)_L$ represent the aerodynamic drag characteristics and lift characteristics of the parafoil, respectively; $F_K$ indicates the parafoil opening force; subscripts of s and w represent the parafoil and the load, respectively.

The aerodynamic characteristics of the opening process of the parafoil meet the following rules[18-19].

Initial inflation section ($0\leqslant t<t_{f1}$)

$$\begin{cases} (CA)_D=(CA)_{D,1}+\beta_1 t \\ (CA)_L=0 \end{cases} \tag{3}$$

Filling section ($t_{f1}\leqslant t\leqslant t_{f2}$)

$$\begin{cases} (CA)_D=(CA)_{D,2}-\beta_2(t-t_{f1}) \\ (CA)_L=\beta_3(t-t_{f1}) \end{cases} \tag{4}$$

where $(CA)_{D,1}$ and $(CA)_{D,2}$ are the resistance characteristics of the initial and end points of the parafoil development stage, respectively; $\beta_1$, $\beta_2$ and $\beta_3$ represent the change slopes of aerodynamic characteristics at each stage, which can be calculated from the aerodynamic characteristics of boundary points at each stage.

$$\begin{cases} \beta_1=\dfrac{(CA)_{D,2}-(CA)_{D,1}}{t_{f1}} \\ \beta_2=\dfrac{(CA)_{D,2}-(CA)_{D,s}}{t_{f2}-t_{f1}} \\ \beta_3=\dfrac{(CA)_{L,s}}{t_{f2}-t_{f1}} \end{cases} \tag{5}$$

where $(CA)_{D,s}$ and $(CA)_{L,s}$ are the drag characteristics and lift characteristics of the parafoil when it is full, respectively; $t_{f1}$ and $t_{f2}$ represent the time of two stages of parafoil opening, which can be expressed as

$$\begin{cases} t_{f1}=\lambda_1 D_0/v_L \\ t_{f2}-t_{f1}=\lambda_2 D_0/v_L \end{cases} \tag{6}$$

where $D_0$ and $v_L$ are the nominal diameter and initial inflation speed of parafoil, respectively; $\lambda_1$ and $\lambda_2$ represent the correction coefficient of two-stage inflation time, which is taken as 5 and 1.8 in this paper, respectively[18].

### 1.2 Model validation

To validate the accuracy of the parafoil flight dynamics model, the flight tests in Ref.[17] is simulated. The parafoil parameters and opening conditions are shown in Table 1, and the aerodynamic characteristics of boundary points in two stages of the opening process are shown in Table 2.

**Table 1 Parafoil parameters and opening conditions**

| Parameter | $A_0$/m$^2$ | $m$/kg | $\theta_k$/(°) | $h_k$/m | $v_k$/(m·s$^{-1}$) |
|---|---|---|---|---|---|
| Value | 60 | 200 | 3 | 530 | 40 |

**Table 2 Coefficient characteristic point value**

| Coefficient | $(CA)_{D,1}$ | $(CA)_{D,2}$ | $(CA)_{L,s}$ | $(CA)_{D,s}$ |
|---|---|---|---|---|
| Value | 0.2 | 48 | 34.8 | 12.6 |

The comparison between the numerical results and literature results are shown in Fig.3. The simulated opening force is consistent with the literature results. As the parafoil deploys, the opening force increases rapidly and reaches the maximum at 0.74 s. At 1.1 s, the parafoil cells start to inflate and the reduction of the drag characteristics lead to the decelerate of the opening force. The maximum opening force obtained in the simulation is 10 554.6 N, occurring at 0.76 s, whereas the maximum force in literatures is 11 061.26 N, occurring at 0.74 s. The relative error of the maximum opening force and the occurrence time is 4.8% and 2.6%, respectively. It shows that the calculation method of parafoil opening dynamics in this paper can predict the opening force accurately.

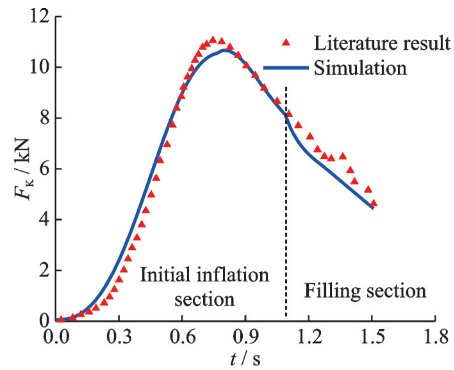



Fig.3 Opening force change curves of opening parafoil

## 2 Dynamic Variation of Parafoil Opening Force

### 2.1 Parafoil parameters and opening conditions

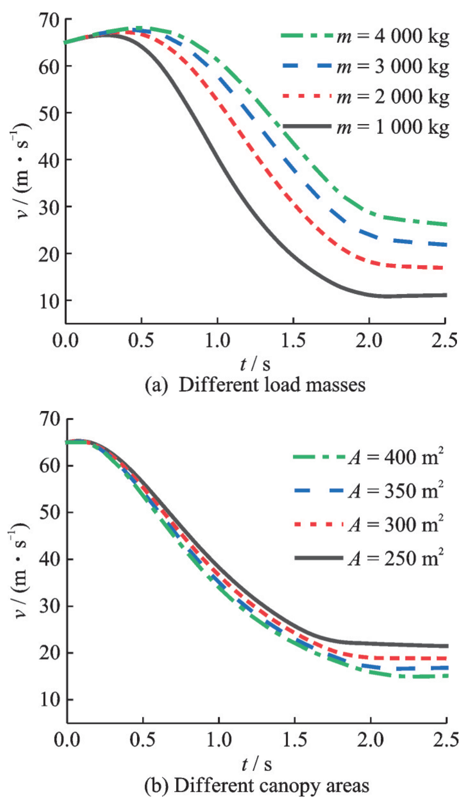
It can be seen from the parafoil opening dynamics equation (Eq.(1)) that the opening process is affected by gravity, inertial force and aerodynamic force, and the parameters affecting the above external forces can be divided into two categories: parafoil parameters (such as load mass and parafoil area) and opening conditions (opening height, opening speed and opening angle). In order to study the influence of various parameters on the parafoil opening force, the research conditions in Table 3 are designed.

**Table 3 Parafoil parameters and opening conditions**

| Condition | Parafoil parameter | | Opening condition | | | Increment |
|---|---|---|---|---|---|---|
| | $M_w$/kg | $A_s$/m$^2$ | $v_k$/(m·s$^{-1}$) | $h_k$/m | $\theta_k$/(°) | |
| 1—4 | 1 000—4 000 | 325 | 65 | 3 550 | 67.5 | 1 000 kg |
| 5—8 | 2 500 | 250—400 | 65 | 3 550 | 67.5 | 50 m$^2$ |
| 9—12 | 2 500 | 325 | 50—80 | 3 550 | 67.5 | 10 m/s |
| 13—16 | 2 500 | 325 | 65 | 10—7 000 | 67.5 | 2 300 m |
| 17—20 | 2 500 | 325 | 65 | 3 550 | 45—90 | 15° |

### 2.2 Influence of parafoil parameters

Fig.4 illustrates the velocity change curves of the system under varying load masses and canopy areas. It is evident that the velocity change pattern remains consistent across different parafoil parameters. During the initial inflation stage, the parafoil is not yet deployed, resulting in a continuous increase in system speed due to inertial forces. Subsequently, the parafoil gradually expands, leading to a steady increase in aerodynamic resistance. Once this resistance exceeds the gravitational force acting on the object, the system experiences a more rapid deceleration. After the air chamber is fully inflated, the lift characteristics of the parafoil gradually surpass its resistance characteristics, causing the parafoil to decelerate more slowly until it ultimately reaches a stable equilibrium speed. The stabilized velocity is directly proportional to the load mass and inversely proportional to the canopy area.

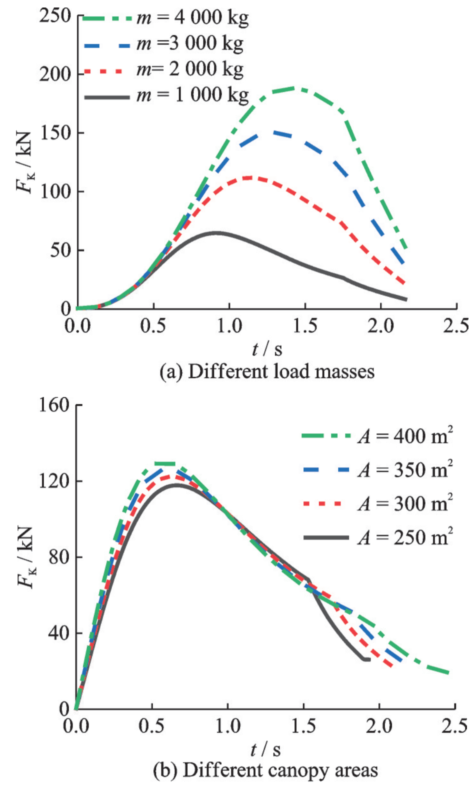


(a) Different load masses

(b) Different canopy areas

Fig.4 Velocity curves of parafoil under varying load masses and canopy areas

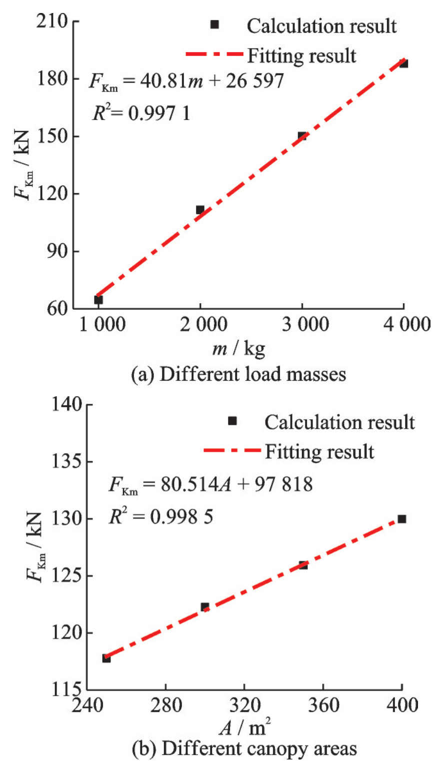
Fig. 5 illustrates the opening force change curves of the system under varying load masses and canopy areas, while Fig. 6 presents the relationship between the maximum opening force and parafoil parameters. It is evident that the maximum opening force occurs during the wing surface expansion phase. It shows a clear relationship with parameters such as load mass and canopy area. Notably, as the



(a) Different load masses

(b) Different canopy areas

Fig.5 Opening force curves of parafoil under varying load masses and canopy areas



(a) Different load masses

(b) Different canopy areas

Fig.6 Maximum opening force curves of parafoil parameters

object weight increases, the airspeed of the system also rises, leading to an increase in both inertial and aerodynamic forces. However, the deceleration time is extended, resulting in a delay in the peak opening force time during parafoil deployment. Conversely, when the canopy area is increased, the aerodynamic force of the parafoil system strengthens, causing a quicker deceleration and an increase in the opening force at deployment, with the peak time occurring earlier. Nevertheless, the larger canopy area also prolongs the parafoil opening time of the system, requiring more time to achieve a stable glide state.

### 2.3 Influence of opening conditions

Fig.7 illustrates the velocity change curves of the system under different opening conditions. It is evident that the velocity change curves exhibit a consistent pattern across various working conditions, although the amplitude of change differs. As the opening speed increases, the deceleration performance of the parafoil system improves, allowing it to reach a stable state more quickly, with the stable speed remaining constant. Conversely, a higher opening height results in lower atmospheric density, which diminishes the aerodynamic deceleration performance of the parafoil, leading to a slower deceleration of the parafoil system. Additionally, the speed at which equilibrium stability is achieved is negatively correlated with both density and height. When the opening trajectory angle changes, it has minimal impact on the inertial and aerodynamic forces during the very brief opening period, resulting in little change in the system's deceleration performance. The trajectory angle primarily affects the horizontal and vertical velocities, thereby influencing the trajectory of the system. During the initial inflation, the attitude angle of the entire system does not change significantly, and the trajectory angle has little effect on the velocity. Once the parafoil begins to fully inflate, its attitude changes under the influence of gravity and lift. As shown in Fig.7(c), a gradual difference in velocity becomes apparent around 0.8 s.

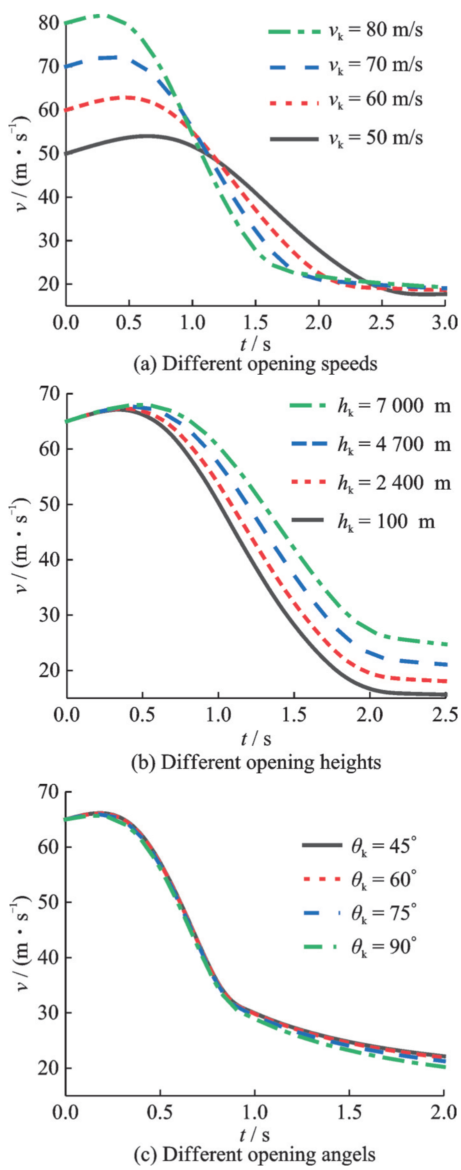



Fig.7 Velocity curves of the parafoil system under different opening conditions

Fig.8 illustrates the opening force change curves of the system under various operating conditions, while Fig.9 presents the relationship curves between the maximum opening force of the system and the operating conditions of the parafoil. It is evident that the maximum opening force during parafoil deployment occurs during the wing surface development phase and exhibits a specific functional relationship with each parameter. Notably, as the opening speed increases, the dynamic pressure experienced by the canopy also rises, leading to a greater volume increment of gas within the canopy during the aeration process. This acceleration allows the aeration process to be completed more quickly, resulting in shorter peak times for opening force and reduced opening times. The maximum opening force during the parafoil deployment is positively

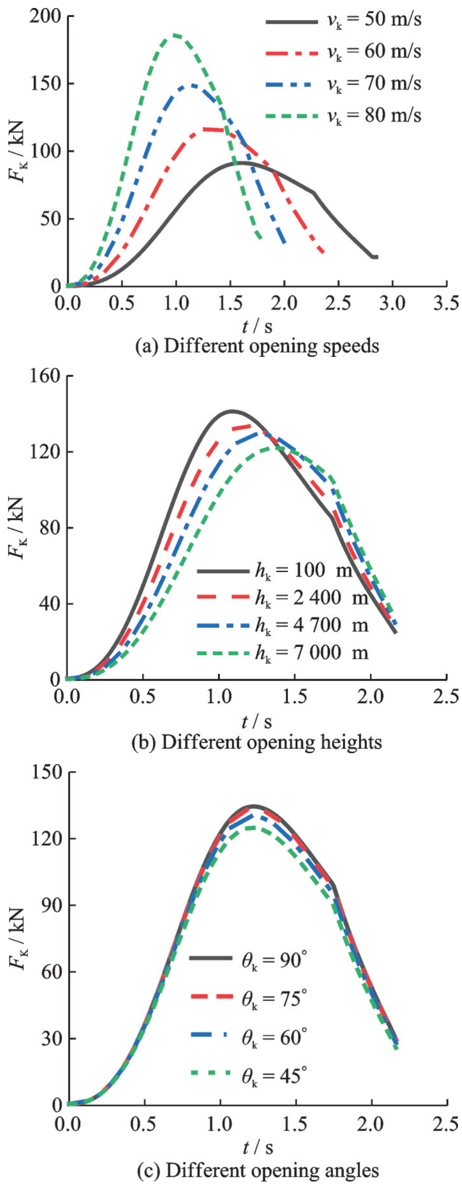



Fig.8 Dynamic load curves of opening parafoil under various operating conditions

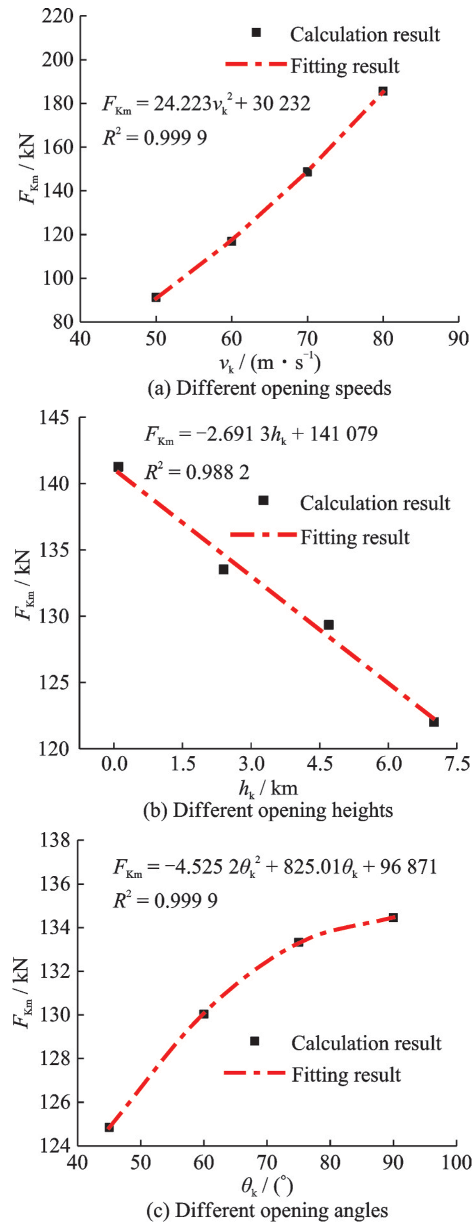



Fig.9 Maximum opening force curves of opening conditions

correlated with the opening speed and follows a quadratic function. Conversely, a higher opening height corresponds to lower atmospheric density, which results in a decreased maximum opening force and a delayed peak time for the opening force. As the trajectory angle increases, the influence of gravity on the aerodynamic direction becomes more pronounced, leading to an increase in the opening force of the parafoil. However, the peak time of opening force and the opening time of the parafoil are minimally affected by the trajectory angle, with the maximum opening force being greatest when the parafoil is deployed vertically.

## 3 Influence Degree of Multiple Factors on Parafoil Maximum Opening Force

### 3.1 Sobol global sensitivity analysis

The Sobol method is a sensitivity analysis method based on variance[20-21] and it quantifies the contribution of each input parameter to the output variability. The maximum open parachute dynamic load model is defined as $F_{Km} = f(B)$, $B = (b_1, b_2, \cdots, b_n)$, where $b_1, b_2, \cdots, b_n$ represent the parameters that affect the maximum opening force, then the spatial domain of the input parameters can be expressed as

$$\Omega^n = (B \mid 0 \leqslant b_i \leqslant 1, i = 1, 2, \cdots, n) \tag{7}$$

The central idea of Sobol method is to decompose the maximum dynamic load model $f(B)$ into the sum of subitems

$$f(B) = f_0 + \sum_i f(b_i) + \sum_{i<j} f_{ij}(b_i, b_j) + \cdots + f_{12\cdots n}(b_1, b_2, \cdots, b_n) \tag{8}$$

where $f_0$ should be a constant, and the integral of each subitem for any variable it contains is zero.

$$\int_0^1 f_{i_1 i_2 \cdots i_s}(b_{i_1}, b_{i_2}, \cdots, b_{i_s}) \mathrm{d}b_{i_s} = 0 \qquad 1 \leqslant n \leqslant s \tag{9}$$

The subitems in Eq.(9) are orthogonal, which can be obtained by $(i_1, i_2, \cdots, i_s) \neq (j_1, j_2, \cdots, j_m)$

$$\int_{\Omega^n} f_{i_1, i_2, \cdots, i_s} f_{j_1, j_2, \cdots, j_m} \mathrm{d}B = 0 \tag{10}$$

All subitems of Eq.(8) can be obtained by taking multiple integrals of Eq.(9).

$$f_i(b_i) = -f_0 + \int_0^1 \cdots \int_0^1 f(B) \mathrm{d}B_{-i} \tag{11}$$

$$f_{ij}(b_i, b_j) = -f_0 - f_i(b_i) - f_j(b_j) + \int_0^1 \cdots \int_0^1 f(B) \mathrm{d}B_{-(ij)} \quad i, j = 1, 2, \cdots, n, i < j \tag{12}$$

where $B_{-i}$ and $B_{-(ij)}$ represent parameters other than $b_i$ and $b_j$, and the total variance of the maximum parafoil opening force function is

$$D = \int_{\Omega^n} f^2(B) \mathrm{d}B - f_0^2 \tag{13}$$

The formula difference can be calculated from each of the terms of Eq.(9)

$$D_{i_1, i_2, \cdots, i_s} = \int_0^1 \cdots \int_0^1 f^2_{i_1, i_2, \cdots, i_s} \mathrm{d}b_i \cdots \mathrm{d}b_s \tag{14}$$

This shows the integral after the square of Eq.(9) in the space domain $\Omega^n$

$$D = \sum_i D_i + \sum_{i<j} D_{ij} + \cdots + D_{12\cdots n} \tag{15}$$

Therefore, the sensitivity of the multi-parameter to the maximum opening force can be expressed as

$$S_{i_1, i_2, \cdots, i_s} = \frac{D_{i_1, i_2, \cdots, i_s}}{D} \tag{16}$$

where $S_{i_m}$ is called the first-order sensitivity coefficient of the factor, representing the single influence of parameter $b_{i_m}$ on the maximum opening force, and the total sensitivity coefficient of the parameter is expressed by the sum of the sensitivity coefficients of various orders of the factor.

$$S_{Ti} = \sum_i S_{(i)} \tag{17}$$

When using the Sobol method for sensitivity calculation, random Monte Carlo arrays $\boldsymbol{A}_{N\times k}$ and $\boldsymbol{B}_{N\times k}$ are generated by independent sampling of the analyzed parameters twice. Here $N$ and $k$ are sampling times and parameter numbers, respectively, and can be calculated by

$$f_0 \approx \frac{1}{N} \sum_{j=1}^N f(\boldsymbol{A})_j \tag{18}$$

$$D \approx \frac{1}{N} \sum_{j=1}^N f^2(\boldsymbol{A})_j - f_0 \tag{19}$$

$$D_i \approx \frac{1}{N} \sum_{j=1}^N f(\boldsymbol{A})_j f(\boldsymbol{B}_A^{(i)})_j - f_0^2 \tag{20}$$

$$D_{-i} \approx \frac{1}{N} \sum_{j=1}^N f(\boldsymbol{A})_j f(\boldsymbol{A}_B^{(i)})_j - f_0^2 \tag{21}$$

Then, by combining Eqs.(16) and (17), the first order sensitivity coefficient and the total sensitivity coefficient of the selected parameter $b_i$ for the maximum opening force can be obtained.

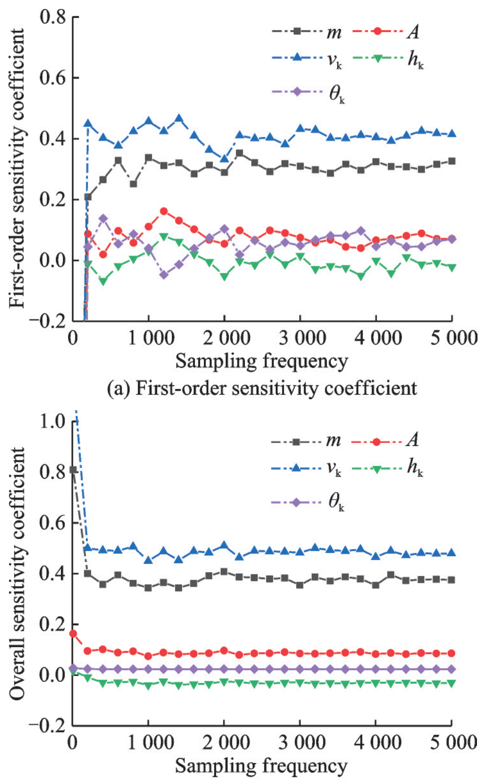
### 3.2 Multi-factor influence degree analysis

When conducting a global sensitivity analysis using the Sobol method, it is essential to first define the range of parameter variations and their probability distributions, followed by the selection of computational samples using an appropriate sampling method. In this study, the variables selected for analysis include load mass $m$, canopy area $A$, the opening speed $v_k$, the deployment height $h_k$, and the deployment angle $\theta_k$. Based on design experience, the upper and lower limits for each parameter are established as shown in Table 4, and it is assumed that the parameters follow a uniform distribution within their specified ranges.

**Table 4 Value scope of each variable**

| Variable | $m$/kg | $A$/m$^2$ | $v_k$/(m·s$^{-1}$) | $h_k$/m | $\theta_k$/(°) |
|---|---|---|---|---|---|
| Max | 4 000 | 400 | 80 | 7 000 | 90 |
| Min | 1 000 | 100 | 50 | 100 | 30 |

Using Latin hypercube sampling[22-23], the first-order sensitivity coefficients and total sensitivity coefficients are calculated for varying sample sizes between 10 and 5 000, resulting in the outcomes shown in Fig.10. It is evident that when the sample size exceeds 4 000, the sensitivity coefficients for all variables converge. The average of the converged results yields the first-order sensitivity coefficients and total sensitivity coefficients for each variable, as illustrated in Fig.11.




(a) First-order sensitivity coefficient

(b) Overall sensitivity coefficient

Fig.10 Sensitivity coefficient vs. sample size

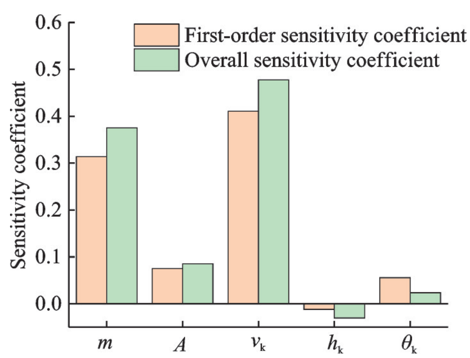



Fig.11 Sensitivity coefficient of each variable

It is evident that within the range of parameter variations employed in this study, the opening speed $v_k$, load mass $m$, and canopy area $A$ of the parafoil significantly influence the maximum opening force during the deployment. Among these, the first-order sensitivity and total sensitivity coefficients for the opening speed are at the highest levels, indicating that it has the greatest impact on the opening force within the specified range. The sensitivity coefficients for both the load mass and the canopy area are relatively high. These two parameters represent the parafoil's structural design, and the load mass exhibits a more pronounced effect. In contrast, the sensitivity coefficients for the deployment height and deployment angle are low, suggesting that their influence on the maximum opening force can be disregarded, and it is noted that deployment height is negatively correlated with the maximum opening force of the parafoil. Furthermore, it can be observed that the first-order sensitivity coefficients and total sensitivity coefficients for $A$, $h_k$ and $\theta_k$ are quite similar, indicating that any one of these three parameters is minimally affected by the interaction with the other four parameters. In contrast, the first-order sensitivity coefficients and global sensitivity coefficients for $v_k$ and $m$ differ significantly, suggesting that these two parameters are notably influenced by their interaction with each other.

## 4 Conclusions

The paper establishes a dynamic simulation model for the opening process of parafoil. The accuracy of the model is validated through literature data, and the velocity and opening force variation patterns during the parafoil deployment process are calculated. Using the Sobol global sensitivity analysis method, the study delves into the impact of five variables—parafoil parameters and opening conditions at the deployment point—on the maximum parafoil opening force. The following conclusions are drawn, and these results provide valuable guidance for parafoil designers, particularly in optimizing deployment conditions to minimize the opening force and enhance the system reliability.

(1) The maximum parafoil opening force occurs during the wing surface expansion phase. It is positively correlated with the load mass, canopy area, the opening speed, and the deployment angle, while it is negatively correlated with the deployment height.

(2) The timing of the maximum opening force

depends on aerodynamic and inertial forces. As the load mass and the deployment height increase, the system decelerates more slowly, delaying the peak opening force. Conversely, an increase in the canopy area and opening speed enhances aerodynamic forces, leading to an earlier peak time for the opening force.

(3) The opening speed is the most critical factor, with a sensitivity coefficient of 0.5. The load mass and canopy area also play significant roles. Together, these three parameters account for over 90% of the influence on the maximum opening force. Additionally, the effects of deployment height and deployment angle are negligible. Therefore, reducing the opening speed, load mass, and canopy area within permissible limits is an effective means to lower the maximum parafoil opening force.

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# 翼伞最大开伞动载影响因素研究

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**摘要:**为探究翼伞开伞过程的动载变化规律及影响因素,本文建立了翼伞开伞过程动力学模型,将翼伞充气过程分为翼面展开段和气室充气段,采用龙格-库塔法进行了翼伞开伞过程的性能计算,计算结果与文献结果规律一致,最大动载误差为4.8%。在此基础上,对20种不同工况下的翼伞系统进行仿真计算,获得了系统运动速度和开伞动载的变化规律,考察了翼伞系统物理参数及开伞工况参数对开伞动载的影响。结果表明,翼伞最大开伞动载出现在翼面展开段,且和物体重量、伞衣面积、开伞速度及开伞轨迹角正相关;与开伞高度负相关。动载峰值出现的时间受气动力和减速惯性力的综合影响,随着物体重量和开伞高度的增加,系统减速变慢,动载峰值出现时间推后;伞衣面积和开伞速度增加,气动力增加,动载峰值时间提前。最后,采用Sobol全局灵敏度分析方法得到了结构参数和开伞工况对翼伞最大开伞动载的一阶灵敏度和总灵敏度系数。结果表明,开伞速度和载荷体质量对最大开伞动载有着重要影响,其一阶灵敏度系数分别为0.410 7和0.313 6,总灵敏度系数分别为0.477 5和0.375 2。伞衣面积的灵敏度处于中间水平,其一阶灵敏度和总灵敏度系数分别为0.074 9和0.085 1。开伞高度和开伞角度的灵敏度系数均接近零,其值的波动对翼伞最大开伞动载影响小。

**关键词:**翼伞;开伞动载;动力学;Sobol法;敏感性分析