1. Introduction

The parachute, a special kind of made-up textile product, has an irreplaceable position in the aviation, aerospace and other fields. During the process of parachute design, the airdropping test is the only means to test whether the design is reasonable. However, the airdropping, which is different from other engineering fabrics’ experiment, needs large capital investment and long development cycle. What is more important is that the airdropping has difficulty in data collection to reveal the parachute working mechanical mechanism.

With the developing of the calculation hardware, the numerical simulation is becoming an important research or design means due to its advantages of economy, flexibility and repeatability. For example, Purvis achieved the two-dimensional coupling calculation by simplified the canopy structure and fluid field model [1]. Stein, Tezduyar et al simulated the parachute opening based on DSD/SST (Deforming Spatial Domain/Stabilized Space Time) coupling model [2–5]. Kim and Peskin proposed the IB (Immersed Boundary) method to simulate the three-dimensional parachute dropping under low Reynolds number [6]. Tutt, Cheng et al used ALE (Arbitrary Eulerian Lagrangian) method to study the parachute opening process [7–9]. Most of the above studies applied the fixed calculation domain, which are applicable to calculate the parachute opening in infinite mass situation such as opening in a wind tunnel. While, if the fixed domain were used to simulate the entire parachute working process (from inflating process to dropping process), the number of elements might be larger and the calculation time might be longer. Moreover it is not advantageous to analyze the flow field by coarsening those elements.

In order to reduce the calculation domain and amount, the finite space surrounding the parachute-payload system was defined as calculation domain. Then the calculation of parachute opening process was carried on in this finite space by FSI method. At last, the abundant flow field and structure field information and the deceleration characteristics curves such as velocity and acceleration were obtained by this method. In order to verify the accuracy of this method, the deceleration characteristics results were compared with experimental results. The moving meshes method could decrease the calculation amount and provide abundant results information. The method used in this paper also could provide a reference for other inflatable fabrics numerical researches.

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C9 parachute, a typical military saving parachute, was set as the simulation object. Then the interaction between the fluid and structure was calculated by explicit finite element method. The entire working process of C9 parachute was calculated in this paper, which was compared with the test results. At last, the numerical results were analyzed and some conclusions were obtained.

2. Model development

2.1 Governing and discrete equations

The finite element model can not only reveal the mechanical essence, but also realize the dynamic simulation. The biggest advantage of finite element model is its accuracy and can be easily integrated into other models. Therefore, it is the main numerical model used to simulate inflatable fabrics working. While, in order to ensure the accuracy of coupling information’s transfer, the fabrics and air were described by Lagrangian finite elements in this paper. Because the Lagrangian finite elements can accurately track the material boundary, the model meets the mass conservation naturally. In addition, the heat transfer is not considered, therefore only the momentum equation needs to be solved (equation 1).

$$\frac{\partial \sigma}{\partial t} = \nabla \cdot \vec{v} + \rho \vec{b}$$  \hspace{1cm} (1)

Where, $\vec{v}$ is the velocity vector, $\sigma$ is the stress vector, $\vec{b}$ is the body force vector, $\rho$ is the density.

According to the virtual work principle, the discrete equation of the above governing equation can be obtained (equation 2).

$$\int_{\Omega} B_i \sigma \, d\Omega - \int_{\partial \Gamma} N_i \rho b \, d\Gamma + \int_{\Omega} N_i \rho \delta \nabla \cdot \vec{v} \, d\Omega = \int_{\Omega} f^m - f^m + Ma = 0$$  \hspace{1cm} (2)

Where, $B_i$ is the geometry matrix represented by index form, $\sigma_i$ is stress, $\vec{b}$ is the external force, $N_i$ and $\psi_i$ are shape functions, $\delta$ the acceleration, $f^m$ is the internal force matrix, $\vec{v}^m$ is the external force matrix, $M$ is the mass matrix, $a$ is the acceleration matrix.

Here, the central difference scheme (equation 3), as most widely used in nonlinear dynamics, was used to discretize the semi discrete equation (2):

$$\vec{v}^{n+1}_i = \vec{v}^n + \Delta t M^{-1} (f^m(d^n, t^n) - f^m(d^n, t^n))$$  \hspace{1cm} (3)

$$= \vec{v}^n + \Delta t M^{-1} f^m$$

Where, $\Delta t$ is the displacement.

2.2 Coupling algorithm

Different form the other continuous medium, fabrics have permeability because of yarn’s crossing and winding. In order to reflect this physical property, the Ergun equation (equation 4) [11–12] was used to calculate the coupling force.

$$\Delta p = [a \cdot \vec{v} \cdot \vec{n} + b \cdot (\vec{v} \cdot \vec{n})^2] \cdot e$$  \hspace{1cm} (4)

Where, $\Delta p$ is differential pressure, $a$ is the linear resistance coefficient, $b$ is the quadratic resistance coefficient, $e$ is the fabric thickness; $\vec{n}$ is normal vector; $\vec{v}$ is the fluid velocity vector through the fabric. The C9 parachute, which is the research object in this paper, is made in MIL-c-7020 type III fabric. The specific coefficients are given by the references [11,13]. Here, the $a$ is 1.5996 kg/m$^3\cdot$s, the $b$ is 4.805e5 kg/m$^3$, and the fabric thickness is 1e-4 m.

Then the coupling force $f_{\text{couple}}$ derived from the equation 4 is applied to both the fluid and fabric in opposite directions to satisfy force equilibrium, and the coupling force $f_{\text{couple}}$ are taken as a part of external force $f^m$ in equation 2.

2.3 Motion and reconstruction of fluid meshes

In order to make the fluid meshes following the motion of parachute-payload system. Three noncollinear nodes was chosen on payload elements (cyan) shown in Fig. 1. The coordinates of these nodes are $x_0$, $x_1$, and $x_2$. A local coordinate system (red) can be defined according to these three nodes, and the axis’s vectors are shown in equation 5.

$$x' = (x_0 - x_2) / |x_0 - x_2|$$
$$z' = x' \times (x_2 - x_0) / |x' \times (x_2 - x_0)|$$
$$y' = z' \times x'$$

The local coordinate system would move after each time step, and a transformation matrix $T$ can be obtained according to the displacement [10]. Therefore, the new homogeneous coordinate of each node on fluid meshes could be calculated based on equation 6.

$$[x_1', x_2', x_3'] = [x_1, x_2, x_3] \cdot T$$  \hspace{1cm} (6)

Where, $[x_1', x_2', x_3']$ is the homogeneous coordinate after the displacement, $[x_1, x_2, x_3]$ is that before the displacement.

According to the coordinates of fluid meshes before and after the displacement, the fluid meshes moving velocity $\vec{v}$ ($\vec{v} = \Delta x / \Delta t$) can be obtained. Then the convection velocity $\vec{c}$ ($\vec{c} = \vec{v} - \vec{\nu}$, where, $\vec{\nu}$ is
materials moving velocity.) which based on flow field meshes as a reference can be calculated. Therefore the materials velocity v in equation 1 is replaced by convection velocity c (equation 7).

\[ \rho v_x + \rho v_y \cdot c_y = \sigma_{x} + \rho b_{x} \]  

(7)

In addition, the fluid elements described by Lagrangian meshes would be distorted in almost every time step. Therefore, it is necessary to reconstruct the distorted fluid meshes by solving the Laplace differential equation 8 [14].

\[ 0 = \alpha \frac{\partial}{\partial x_{i}} x + \alpha \frac{\partial}{\partial x_{i}} x + \alpha \frac{\partial}{\partial x_{i}} x + 2 \beta \frac{\partial}{\partial x_{i}} x + 2 \beta \frac{\partial}{\partial x_{i}} x + \beta_{i} \left( \frac{\partial}{\partial x_{i}} x \cdot \frac{\partial}{\partial x_{i}} x \right) + \beta_{i} \left( \frac{\partial}{\partial x_{i}} x \cdot \frac{\partial}{\partial x_{i}} x \right) \]

\[ \beta_{i} = (\partial_{x_{i}} x \cdot \partial_{x_{i}} x) (\partial_{x_{i}} x \cdot \partial_{x_{i}} x) \]

\[ \frac{\partial}{\partial x_{i}} x \cdot \frac{\partial}{\partial x_{i}} x \]

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\[ \frac{\partial}{\partial x_{i}} x \cdot \frac{\partial}{\partial x_{i}} x \]

After the meshes reconstruction, the convection terms \( \phi \) (such as mass, momentum and other flow field information) were updated based on FVM (Finite Volume Method), and its three dimensional form is shown in equation 9.

\[ \frac{\partial \phi}{\partial t} + \frac{\partial \phi}{\partial x_{i}} = 0 \]  

(9)

The discretization and solution of the convection equation 9 employed the MUSCL (Monotone Upwind Schemes for Conservation Laws) scheme [15] with second order accuracy in this paper.

3. Example

The typical C9 parachute was taken as the research object. The flattened canopy structure are shown in Fig. 2. The whole canopy was sewed by 28 gores. The diameter of central vent is 0.835 m. The nominal diameter and area of canopy are 8.5 m and 57.2 m² respectively. The length of each line is 7 m.

According to the above structure parameters, the finite element model was established by using pre-processing software HYPERMESH. The canopy was discretized by triangular elements (1,4000). The lines were discretized by bar elements (1,932). Meanwhile, a local coordinate system was established on payload model (Fig. 3).

In this paper, the fabrics described by finite elements were treated as continuum and the mechanical properties of yarn layer were homogenized. Therefore, the one dimensional linear elastic constitutive equation was used to simulate the lines:

\[ \sigma = E \varepsilon \]  

Where, \( \sigma \) is Cauchy stress, \( \varepsilon \) is strain, \( E \) is Young’s modulus.

While, the canopy present small strain and large rotation in parachute working. The canopy large deformation effect mainly caused by fabric large rotation. Therefore the Saint Venant Kirchhoff
constitutive equation was used to describe the fabric, and which was widely used in parachute dynamic simulation [7‒9, 11‒12].

\[ S = \lambda \text{trace } E I + 2\mu E \]  

(11)

Where, \( S \) is Second Piola-Kirchhoff stress, \( \lambda \) and \( \mu \) are Lame coefficients, \( E \) is Green strain.

Then the Cauchy stress \( \sigma \) used in above governing equations can be obtained by:

\[ \sigma = J^{-1}F : S : F^T \]  

(12)

Where, \( F \) is deformation gradient, \( J \) is Jacobian determinant.

In addition, the canopy was discretized by three nodes shell elements and the fabric material anisotropy was neglected in this paper. Finally, the constitutive equation 11 in Voigt matrix form is shown by:

\[
\begin{bmatrix}
S_{11} \\
S_{22} \\
S_{12}
\end{bmatrix} = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix}
1-\nu & \nu & 0 \\
\nu & 1-\nu & 0 \\
0 & 0 & 1-2\nu
\end{bmatrix} \begin{bmatrix}
E_{11} \\
E_{22} \\
E_{12}
\end{bmatrix}
\]  

(13)

Where, \( \nu \) is Poisson ratio.

The C9 parachute is made in MIL-c-7020 type III fabric, and the material parameters of which are shown in Table 1 [11,13].

| Material parameters          | Value |
|------------------------------|-------|
| Density of canopy (kg/m³)    | 533   |
| Elastic modulus of canopy (Pa)| 4.3e8 |
| Density of line (kg/m³)      | 462   |
| Elastic modulus of line (Pa) | 9.7e10|

It was unnecessary to establish the body fitted flow field meshes in this paper, therefore the flow field domain was divided by hexahedral meshes (1,150,000). And the fluid meshes and structure meshes interspersed with each other. The specific size is shown in Fig. 4.

Here, the parachute snatch velocity was less than 0.3 Maher number. Therefore, the air can be considered as incompressible material, and the stress description is divided into deviatoric part and hydrostatic part. The constitutive equation of air is shown in equation 14, and which must be used together with the ideal gas state equation:

\[ \sigma_{ij}^{\text{dev}} + \sigma_{ij}^{\text{hydr}} = \mu (v_{ij} + v_{ji}) - p \delta_{ij} \]  

(14)

Where, \( \mu \) is dynamic viscosity coefficient, and \( p \) is hydrostatic pressure.

In order to compare with the airdropping test (Fig. 5), the working conditions applied in calculation is shown in Table 2. The entire parachute dropping simulation consumed 246 hours based on Inter i7 4770 K processor (total Memory is 16 GB).

![Fig. 4 Fluid meshes and model size](image)

**Fig. 5** Schematic drawing of air dropping test (where, \( \theta \) is contrail declining angle, \( v_s \) is snatch velocity)

| Working conditions of calculation | Value |
|-----------------------------------|-------|
| Opening altitude (m)              | 1830  |
| Atmospheric pressure (Pa)         | 8.12e4|
| Atmospheric density (kg/m³)       | 1.023 |
| Payload (N)                       | 980   |
| Snatch velocity (m/s)             | 20    |
| Contrail declining angle (°)      | 90    |

4. Comparison between calculation and test results

4.1 Dynamic load comparison

The reference [16] provides the dimensionless
It can be found that the calculation results were consistent with the dropping test. The entire process can be divided into three phases.

**The pre-inflation phase (0.0–0.41)**: With the opening of canopy, the aerodynamic deceleration area and dynamic load increased. When the vent of the parachute fully opened, the first peak appeared in both numerical and experimental results.

**The fully inflation phase (0.41–1.0)**: After the vent was fully opened, the decelerating effect was significant. Therefore the dynamic load began to decline after the first peak. When the lower part of the canopy expanded, the deceleration area reached the maximum value and the second peak appeared.

**The stable dropping phase (after 1.0)**: When the deceleration shape was stable, the dynamic load decreased followed the velocity’s decreasing.

We also found that the dimensionless load curve of calculation was slightly higher than the test curve, because the contrail declining angle in this work was 90° while the test angle was less than 90° in actual dropping. It is proved that the dynamic load of 90° is greater than other angles based on a large number of tests.

### 4.2 Deceleration area comparison

The reference [16] also provides the data of deceleration area change (Fig. 7).

It could be found in Fig. 7 that the results of numerical simulation were consistent with the test, but there were still some errors between them. The errors were mainly caused by two aspects. On the one hand, the contrail declining angle in this work was 90°, which was bigger than it in test. Therefore, the canopy would expand slightly faster than tests results. On the other hand, the calculation data could be directly obtained, while the tests were indirectly obtained by measuring the video pictures which exist more man-made errors.

In addition, in the actual parachute opening process, the canopy would form a ‘squid’ shape after the vent was fully opened, and the inlet would transiently shrink. After the canopy was fully inflated, the area would continue to increase because of the inertia force. These details were significant in calculation, while the test results were difficult to reflect the above details.

### 5. Analysis of numerical results

Fig. 8 shows the equivalent stress, flow velocity. Fig. 9 shows the velocity and acceleration of payload.

According to the above numerical results, the entire parachute dropping process was analyzed.

(1) In pre-inflation phase, the canopy bottom was opened firstly, and airflow into the canopy easily. The canopy inflated uniformly, the stress on the canopy was low. A symmetric vortex began to appear at the external flow field of canopy bottom (Fig. 8a). Meanwhile, the canopy had not yet formed an effective aerodynamic deceleration surface. Therefore

\[
\text{a. } t=0.12 \text{s (} t/t_f=0.14) \text{.}
\]
the deceleration effect was not obvious (Fig. 9).

(2) That the vent was completely opened denoted the end of the pre-inflation phase. And the first peak of acceleration appeared (Fig. 9). The canopy appeared ‘squid’ shape, the stress mainly concentrated on the top part and the area where the folds began to expand. At the moment, the canopy top provided the main deceleration force. The outside vortex gradually rose to the canopy top and become asymmetric because the bottom of canopy was not fully expanded (Fig. 8b).

(3) In fully inflation phase, the canopy expanded from top to bottom gradually. Followed with this change, the stress concentration region also broadened. The vortex outside of the canopy became more symmetrical (Fig. 8c). The deceleration effect began to be obvious in this phase (Fig. 9).

(4) When the canopy was completely opened, the deceleration force reached the maximum value (Fig. 9). At this moment, the stress mainly concentrated on middle part of each gore and individual unexpanded folds. The air flowed out from inside of canopy mixed with outside airflow, and formed a stable symmetric vortex (Fig. 8d).

(5) In stable dropping phase, the velocity of payload maintained at 6.1 m/s gradually, and the acceleration of which tended to 0 m/s² (Fig. 9). The velocity was consistent to the actual stable dropping velocity, about 6 m/s. The stress began to decrease and the flow field tended to be stable. The canopy appeared ‘breathing’ phenomenon.

6. Conclusions

In this paper, the moving mesh method was applied to simulate the dropping process of C9 parachute. The accuracy and reliability of this numerical method was verified by test results. This method used in this paper could obtain transient change of flow field and canopy structure. It has some directive significance in preventing parachute working failure and improving parachute design level by analyzing those numerical results. This method also could be a reference in other inflatable fabrics design.

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**Fig. 8** Results of structure and flow field

**Fig. 9** Acceleration and velocity of payload
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