Research on Wingtip Collapse of Parafoil

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Abstract

Aiming at the wingtip collapse problem, the nonlinear cable-membrane finite element model of parafoil was established based on the large displacement-small strain characteristics of structure. Combined with the previous CFD result, the three-dimensional deformation of parafoil was numerically simulated. The results show that the span in flight decreases compared with its design value; the maximum thickness of airfoil profile increases after bumps appear, and extra angle of attack and sweepback arise from canopy deformation. Due to the flexibility of canopy, the wingtip collapses under the critical crosswind load, and simultaneously the cells get squashed and the suspending lines become slack.

Keywords

Parafoil; membrane element; cable element; wingtip collapse.

1. Introduction

The parafoil is a flexible wing which maintains the aerodynamic shape by the ram-air in cells. As a kind of new aerodynamic decelerators, it receives the universal attention in space recovery technology. The use of parafoil become more and more extensive. The parafoil system is composed of flexible canopy and flexible suspending lines, so the parafoil presents obvious deformation in flight. The wingtip collapse problem of flexible parafoil under crosswind may cause accidents.

Since the test is high-cost, the numerical simulation has become a popular way to analyze the deformation of parafoil. Kalro[1] set the appearance of deformed canopy according to the drop test and analyzed the motion of opening process. Eslambolchi[2] extracted inflated canopy geometry from close-up images of the MC-4 canopy in flight, and computed the flowfield around the deformed canopy.Ibos[3] simulated the fluid-structure interaction problem of the parafoil by SINPA software. Kalro[4] calculated the appearance of parafoil in steady flight using the parallel coupling algorithm of the fluidic and structural finite element methods. Fogell[5] analyzed the fluid-structure interaction problem of a single-cell parafoil model. Altmann[6] studied the deformation of canopy by the potential flow theory and the cable finite element. Peralta[7] investigated the geometry of a fully inflated canopy in steady flight using a prescribed pressure distribution.

This article aims at the deformation of canopy in steady flight and the bearing compressive capacity of deformed canopy under crosswind. Based on the previous CFD simulation, the nonlinear cable-membrane finite element model of parafoil was established. The features of deformation were analyzed and the outline of canopy collapse was presented.

2. Methodology

The simulation object is a rectangular parafoil, whose design parameters are presented as follows: the baseline airfoil is Clark-Y18, the number of cells is 15, the span length is 2.4m, and the chord length is 0.8m. The ideal geometry of this simulation object is shown in Fig. 1.

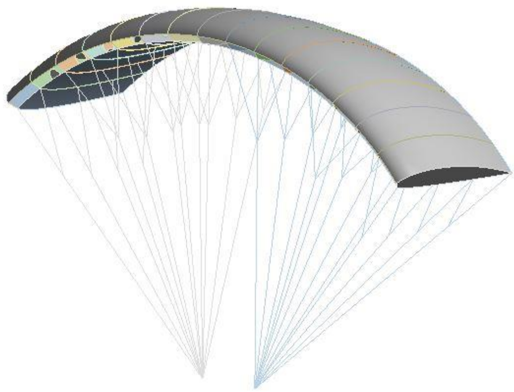

Fig. 1 Ideal geometry of simulation model

The Finite element method is the most widely used numerical algorithm for structural analysis. The parafoil is generally made of textile material, so its bending stiffness can be ignored and it bears the load by deformation. With the structural characteristics of large displacement and small strain, the deformation of parafoil belongs to the geometric nonlinear problems in finite element method. The incremental form of matrix equation for the analysis of geometrical nonlinear problem using the U.L. format is given below:

$$({}_t^t\boldsymbol{K}_L + {}_t^t\boldsymbol{K}_{NL})\boldsymbol{u} = {}^{t+\Delta t}\boldsymbol{Q} - {}_t^t\boldsymbol{F} \tag{1}$$

Where: $\boldsymbol{u}$ is the increment vector of node displacement; ${}_t^t\boldsymbol{K}_L$ is the tangent stiffness matrix; ${}_t^t\boldsymbol{K}_{NL}$ is the initial stress stiffness matrix; ${}^{t+\Delta t}\boldsymbol{Q}$ is the node load vector; ${}_t^t\boldsymbol{F}$ is the equivalent load vector of Kirchhoff Stress Tensor.

The suspending lines of parafoil are simulated by one-way cable element which is more matching with the structural characteristics of lines. Compared to the shell element, the membrane element can preferably simulate the canopy structure of parafoil because the membrane element is not able to bear bending moment. To ensure the proper shape of cell opening and to accurately simulate the structure of parafoil, reinforcing bands with a width of 1 cm were attached to the front of the upper and lower surfaces and the rib cuts, and the reinforcing bands were also simulated by one-way cable element. The meshes of the parafoil are illustrated in Fig. 2. The canopy is divided into triangular membrane elements. The number of elements is 110000 and the number of nodes is 60000. The number of cable elements for the suspending lines and the reinforcing band is 819 and the number of nodes is 1610. The two intersection points of suspending lines are fixed. To avoid the motion of rigid body, the symmetrical boundary condition is applied at the centre of parafoil.

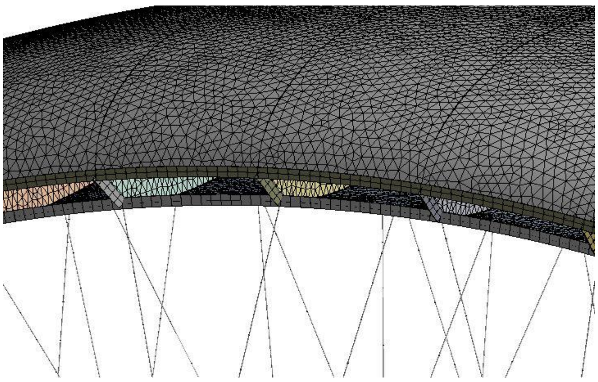

Fig. 2 Sketch map of parafoil grid

The pressure distributions on internal and external surface of canopy, which are simulated at the angle of attack of 5 °using Fluent software, are applied on the parafoil structure by the interpolation map. In order to avoid divergence, the load is applied on the canopy in the way that it increases linearly with substep.

3. Result and discussion

The material of the canopy is MIL-C-7020 III[8]. Its elastic modulus is 430 MPa and its Poisson's ratio is 0.14. The thickness of the canopy is 1 mm. The diameter of the lines is 1mm and its material is Kevlar29. The elastic modulus of this material is 97 GPa. The 2-millimeter-thick reinforcing band is made of aramid, whose elastic modulus is 400 GPa. Fig. 3 shows the displacement distribution contour. The deformation contour is not amplified and has true scale with geometric dimensioning of canopy.

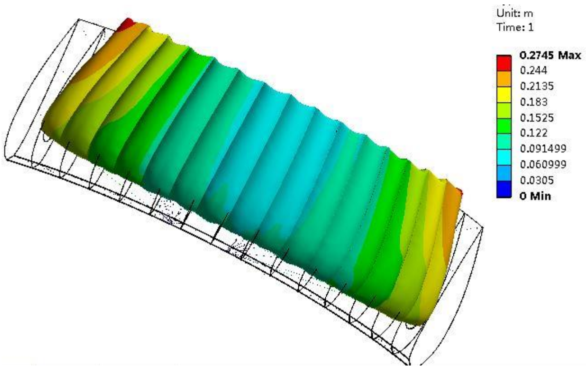

Fig. 3 Displacement distribution contour of parafoil

Fig. 3 illustrates that the inflated canopy reduces the span by 0.32 m which equals to the width of two cells, so the actual span in flight is reduced by 13% as compared with the designed span. At the same time, due to the role of aerodynamic drag, the entire canopy moves back from the ideal design position, and the backward displacements at the wingtips are greater. The shape of the canopy is no longer a rectangle, but is bent backwards to provide an extra angle of sweepback of about 2°. Due to the restraint characteristic of suspending lines, the maximum displacement is 0.27 m and occurs at the trailing edge of the wingtip. When the cell is inflated, the upper and lower surfaces of the cell must be bent to bear the load, and the width of each cell will be reduced. The flexible lines can only restrict the relative position of the intersection point of the lines and the connection point of the ribs, resulting that the ribs can move easily on the arc whose center is the intersection point and radius is the line length. The move is similar to the contraction of the accordion and leads to large difference between the actual shape and the design shape of parafoil.

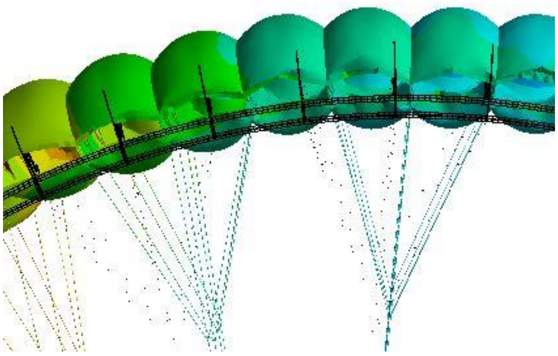

Fig. 4 Front view of parafoil deformation

The front view of the deformation of parafoil is shown in Fig. 4. It shows that the canopy and suspending lines shift along the spanwise direction as mentioned above, while the leading edge has a small upward movement lead to an additional angle of attack about 1.4°. This is because the aerodynamic pressure of canopy is mainly at the front and the parafoil rotates in the pitch direction under the constraints of the flexible lines. There are some wrinkles at the openings, caused by the small difference between internal and external pressure. These wrinkles may cause a risk of closing the opening and collapsing the cells. The bumps on the canopy are obvious. The maximum thickness of the airfoil is 18%c, but it will increase to 26%c after the bumps appear.

The linear buckling theory is not appropriate for structural stability analysis of parafoil under crosswind because of the strong structural nonlinearity of parafoil. The crosswind was assumed as pressure load on the wing tip, and then the nonlinear buckling analysis of deformed canopy was implemented. According to the curve between the displacement and the pressure load, the critical pressure for deformed canopy is 32.9 Pa, corresponding to the crosswind speed of 7.3m/s.

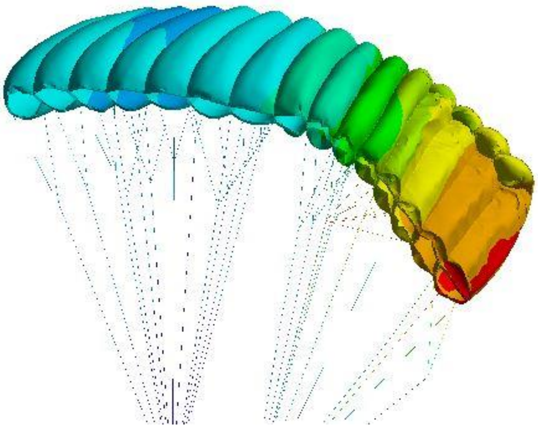

Fig. 5 Simulation result of the parafoil collapse

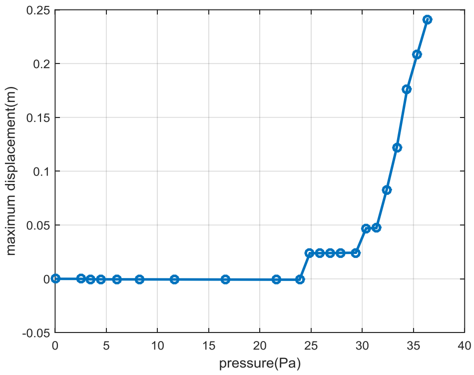

Fig. 6 Load-displacement relationship of deformed canopy

Fig. 5 shows the simulation result of the collapsed parafoil. The cells of right wingtip get squashed and the suspending lines are slack. The left wingtip maintains the correct shape, but the right wingtip under the crosswind pressure is collapsed. The canopy can't produce the lift and may cause accident.

4. Conclusion

A three-dimensional simulation for the aerodynamic deformation of parafoil was conducted in this paper. The results show the span of deformed canopy is approximately 13% less than its designed value and the maximum thickness of airfoil profile become 26%c rather than 18%c on account of the bump formed by cell inflating. Furthermore, the backward displacements of wingtips caused by drag create an extra angle of sweepback of 2 °.The deformed canopy can withstand crosswind until 7.3m/s. When the wingtip is collapsing, the cells get squashed and the suspending lines are slack.

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