Research on Aerodynamic Performance of Oversize Modular Parafoil in Random Wind Field

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Abstract

This article focuses on the research of oversize modular parafoil, extracting two key factors, wind speed and direction, for the wind field environment during parafoil flight. This article selects the rate of wind direction change as the sole variable, mainly studying the impact of gusts on the aerodynamic performance of oversize modular parafoil. This paper uses the UDF method to define a gust model at the boundary of the incoming flow of parafoil, simulates the changes in gust during actual parafoil, and analyzes the aerodynamic interference phenomena experienced by three-dimensional.

Keywords: CFD method, oversize modular parafoil, random wind field, unsteady turbulence, UDF

1. Introduce

Due to the fact that parafoil requires long-term aerial operation and that the working environment of parafoil is mostly in the troposphere. The atmospheric condition in this environment is quite complex since situations such as wind shear and gusts may exist. The complex environment has a significant impact on the aerodynamic characteristics of parafoil;therefore it is necessary to study the aerodynamic performance of parafoil under the influence of complex atmospheric environments. This article mainly analyzes the impact of gusts on the aerodynamic performance of parafoil.

During the execution of missions, parachutes are inevitably subject to unfavorable weather conditions. Many scholars have examined the response of paragliders in wind and rain conditions. Huang established a method for calculating the impact force and torque of raindrops on aircraft based on the momentum theorem[1]. The results indicate that rainfall can reduce the lift of aircraft, increase drag, and increase the equilibrium angle of attack. Xu simulated gust conditions by introducing the "grid velocity" method[2]. The results indicate that as the aspect ratio increases, the lift coefficient response of the wing under gust action will increase. The aerodynamic response amplitude at the root of the wing is greater than that at the tip of the wing. Nie established a reduced order model (ROM) for aerodynamic load state space under gust excitation[3]. The results indicate that the model predictive controller effectively suppresses the wing root bending moment output under continuous gust excitation during transonic flight. Thompson measured the lift, drag, and moment coefficients of rectangular planar wings with wettable and non-wettable surface coatings under light to moderate rain conditions[4]. Research has found that the influence of droplet and waterline diameter on aerodynamic performance is more important than the location of waterline formation. Karpel proposed an analysis and design technique for active flutter suppression and gust mitigation control systems[5]. It can be used to design constant gain, partial feedback control systems, while ensuring stability and optimizing any expected combination of gust response parameters throughout the entire flight envelope. Singh improved the unsteady Euler solver to calculate the indicated response of rectangular wings to changes in attack angle step[6]. Research has found that using computational fluid dynamics to directly calculate indicator responses can yield fairly accurate results. Raveh proposed two methods for analyzing the gust response of free elastic aircraft based on computational fluid dynamics[7].

At present, the research on the aerodynamic performance of parafoil in complex environment mainly focuses on the influence of wind and rain on the aerodynamic performance of parafoil. The study of the parafoil flight process by raindrops has been relatively comprehensive and systematic. The study of the influence of the parafoil on wind field changes mainly focuses on the analysis of the aerodynamic performance of the parafoil under wind shear. However, the wind shear is quite different from the actual working environment of the parafoil, and it cannot well simulate the wind direction changes encountered during the actual flight of the parafoil. As a result, according to the wind field environment during parafoil flight, two key factors of wind speed and wind direction are extracted, and the wind direction change rate is selected as the only variable to study its influence on the aerodynamic performance of the parafoil.

2. Numerical calculation methods

2.1 Governing equation

The governing equation of the parafoil is the N-S equation, and the expression for the direction of the horizontal axis (x-axis) in the spatial Cartesian coordinate system is:

$$\frac{\partial(\rho u_i)}{\partial t} + \mathrm{div}(\rho u_i u) = -\frac{\partial p}{\partial x} + \mathrm{div}(\mu \mathrm{grad}\, u_i) + S \quad (1)$$

where $\mathbf{u}$ is the velocity vector and ρ is the density; t is the time; u_i represents the component of velocity on the x-axis; p is the pressure on the fluid microbody; μ is dynamic viscosity; S is a generalized source term.

Due to the unclosed nature of the average N-S equation, a turbulence model is introduced to close the equations. However, the standard K-epsilon turbulence model has good stability and economy, as well as high calculation accuracy; therefore it is the most widely-used turbulence model. At the same time, the model also has good robustness, which is suitable for initial iteration, design selection and parameter research.

2.2 Establishment of an oversized parafoil model

In this paper, the aerodynamic performance of the oversize modular parafoil is studied by taking the 836m^2 parafoil as an example, and the size parameters are shown in Table 1.

Table 1-Dimension parameter table of oversize parafoil.

	Canopy area/m2	Span length/m	Chord length /m	Number of cell
Oversize parafoil	836	52.25	16	14+11+13+11+14

The oversized combination parafoil consists of two 11 chamber paragliders, two 14 chamber parafoil, and one 13 chamber parafoil, with a total of 63 chambers connected by 58 load-bearing ribs to the upper and lower wing surfaces. At the same time, the connection method of the oversized composite parafoil is to uniformly select 9 nodes on the upper wing surface, and select 7 nodes (excluding the points at the leading and trailing edges) connected to the parachute rope on the lower surface for common node connection. The central plane of the middle chamber along the spanwise direction is defined as the axial plane, and the entire canopy is symmetrical along the axial plane. The maximum spacing at the combination is 0.288 mm. The model is shown in Figure 1.

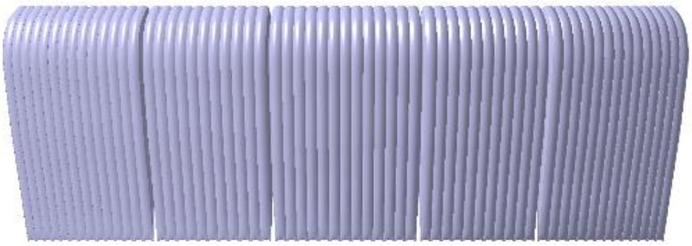


Figure1-Oversize modular parafoil without pull-down model.

The ram-air parachute studied in this article approximates a smooth wall with incoming flow velocity v=20 m/s，reynolds number Re=ρ•v•d/μ=2.19×10^7（where v and d represent the flow velocity and characteristic length of the fluid）The aerodynamic calculation in this article can be reasonably assumed as a steady incompressible turbulent flow, and the K-epsilon standard turbulence model is used for solution.

2.3 Verification of accuracy of calculation methods

At present, although computational fluid dynamics (CFD) methods are developing rapidly, the results may be affected by factors such as mesh, parameters, and model algorithms, resulting in certain numerical errors. Therefore, experimental verification is needed. Due to the limited research on ultra large parachutes and the lack of suitable experimental data as a reference for simulation calculations, this paper refers to other parachutes with the same airfoil to verify the numerical simulation method proposed in this paper. Desabrais selected the MC-4 paraglider commonly used by the US military as the research object for wind tunnel tests and airdrop tests, respectively. The paraglider model used in this experiment is a semi-rigid model, which establishes sturdy wing ribs and uses flexible fabric as the material for the parachute cover. The flow of air around the paraglider is observed through tufts arranged on the parachute cover[8].The experiment was conducted at the MIT Wright Brothers Wind Tunnel, which is a closed reflux continuous flow wind tunnel. The airflow velocity in the wind tunnel is set to 12.0 m/s, resulting in a Reynolds number $Re=8.2\times10^5$. The physical images are shown in Figures 2 and 3. The experimental approach is rigorous, the method is scientific, and the results are reasonable. Therefore, referring to the wind tunnel tests conducted by Desabrais, the rationality and applicability of the model in this paper are verified. The independence of the grid and the accuracy of the simulation calculation method is verified, too.

Figure 2-Internal structure of wind tunnel model.

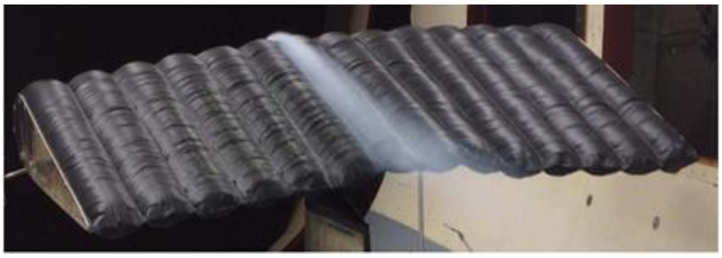


Figure 3-Photos of the wind tunnel model during the testing process.

2.4 Turbulence applicability verification

This article refers to the model data in the above literature to establish a three-dimensional parafoil simulation model, and selects the same airfoil as the rib section and set up 14 half chambers, each with a width of 0.143 m. The wingspan of the parachute is 2 m, the chord length is 1 meter, the aspect ratio is 2:1, and the area is 2 m^2. The 3D simulation model is shown in Figure 4.

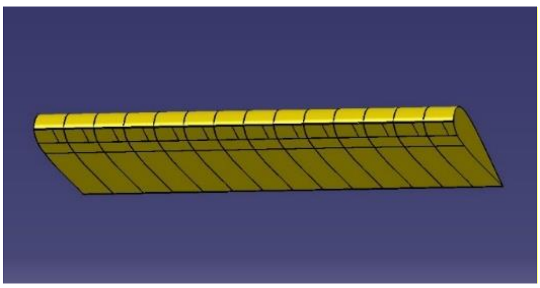


Figure 4-3D Parachute Simulation Model.

This article chooses the relatively stable attack angles of 2 ° and 8 ° during paraglider flight as references for CFD simulation calculation, sets an angle of attack every 2 ° for a total of four operating conditions, chooses the Reynolds averaged N-S equation as the control equation, and uses the finite volume method as the discretization method. This article selects the commonly used one equation model S-A model, two equation k - ω SST model, and k - ε standard model in computational fluid dynamics for turbulence independence verification.

Due to aerodynamic interference, air friction, and other factors during the experiment, the overall resistance instability of the paraglider is significant. Therefore, this article selects the lift coefficient, which has a decisive impact on the aerodynamic performance of paragliders as a comparative parameter. This article simulates and calculate the operating conditions at different angles of attack under a certain inflow velocity, and compares the obtained simulation results with the wind tunnel test results in the literature, as shown in Figure 5. Considering the calculation cost and the main analysis object, it is assumed that the parafoil model is rigid and that the breathability of the canopy is 0 during the calculation process.

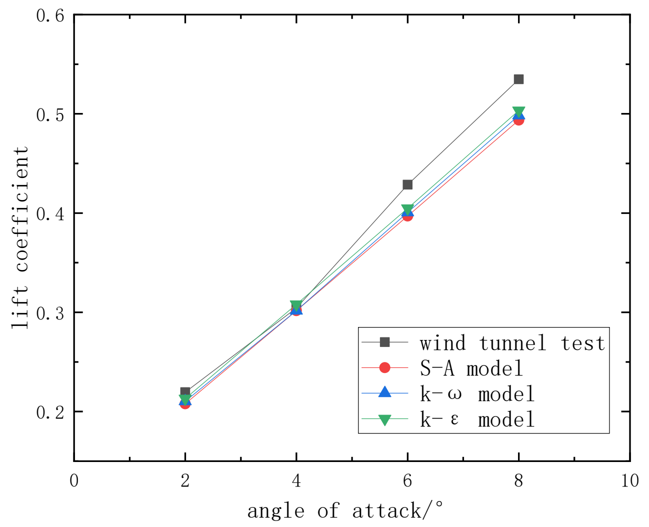


Figure 5-Comparison of wind tunnel test and simulation results.

The simulation results of the parafoil lift coefficient are very close to the wind tunnel test results. The minimum deviation occurs at an angle of attack of α =4° .The deviation at α =8° is slightly larger. The simulation results of different turbulence models are very close. The calculation results of the k-ε standard model are closer to the wind tunnel test results. The minimum error is only 1.22%. At maximum of the value is 5.89%. Compared to the one equation model SA model and the two equation k - ω SST model, the error is smaller. It can verify the rationality of choosing the k - ε standard model in this article.

There are many reasons that can lead to errors between simulation results and wind tunnel test results, such as the difference between the nonlinear dynamic structure of the flexible parafoil used in the experiment and the rigid structure used in the simulation, the difference between the bulging structure after the parafoil is opened in the experiment and the non-bulging structure in the simulation, the processing errors, measurement errors, environmental factors, and other issues of the test piece during the experiment, as well as the model errors, rounding errors, truncation errors, and so on in the simulation calculation process. Therefore, this is within an acceptable range, which proves that the numerical simulation method in this paper has high accuracy in the aerodynamic performance of paragliders.

2.5 Grid independence verification

To ensure that the number of grids in the calculation process does not affect the calculation results, grid independence verification is carried out based on the previous section. Establish multiple different grid models with a range of grid sizes 3.3×10^5~2.2×10^6. Taking the calculation condition at α=4°as an example, the calculated lift coefficient is compared with the wind tunnel test results, and the error is shown in Table 2.

Table 2-Grid independence verification.

	Wind tunnel test	3.3×10^5	9.0×10^5	1.78×10^6	2.55×10^6
Lift coefficient	0.3043	0.3123	0.3113	0.3016	0.3096
error/%	0	2.63	2.31	0.89	1.74

From the table, it can be seen that the simulation results obtained with different grid sizes have very small errors compared to wind tunnel tests. It can be explained that the calculation result is independent of the number of grids. Taking into account issues such as computational accuracy and cost, a grid size of 1.78×10^5 was chosen as the method for establishing the grid model in this paper.

3. Analysis of oversize modular parafoil in complex atmospheric environments

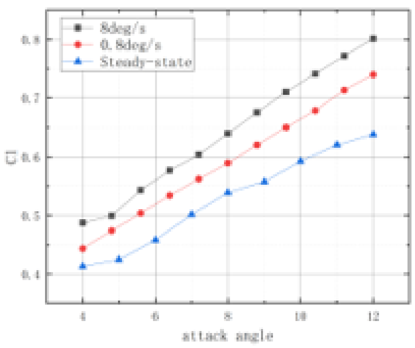
3.1 Simulation settings

This section uses the UDF method to define a gust model at the boundary of the incoming flow of a paraglider, simulates the changes in gust during actual paragliding, and analyzes the aerodynamic interference phenomenon experienced by three-dimensional paragliders during gliding under gust conditions. Due to oversize modular parafoil reaches maximum lift to drag ratio at around 8 ° angle of attack, this section selects 4°-12° as the range of angle of attack variation.

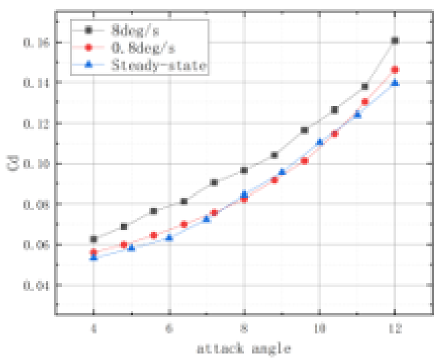
3.2 Aerodynamic performance analysis

This section investigates on the aerodynamic performance of oversized modular parafoil under continuous changes in incoming wind direction, and compares the results with the steady-state calculation of a fixed angle of attack with unchanged wind direction, analyzes the reasons for the differences.

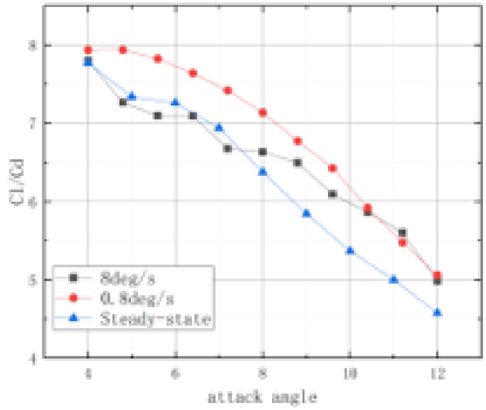
This section compares the two sets of calculation results with the steady-state results, and the results are shown in Figure 6. Relatively speaking, when the angle of attack changes by 0.8 ° per second, it is closer to the steady-state calculation results. The difference becomes more pronounced when changing to 8 ° per second. From the perspective of lift coefficient, the faster the wind direction changes, the larger the lift coefficient value is. The maximum lift coefficient for an 8 ° angle of attack change per second reaches 0.80. However, the maximum lift coefficient for steady calculations is only 0.63. The increase reaches 26%. The increase in case at 0.8 ° per second is only 16%. But from a trend perspective, all three conditions show a monotonically increasing trend. And the increase and slope are the same. The condition with a change in attack angle of 0.8 ° per second is very close to the steady result. Two conditions alternate in ascending with slight differences. The overall difference is not significant. When the wind direction changes to an angle of attack of 8 ° per second, there is a significant increase in the drag coefficient. But the growth trend is the same as the first two working conditions. The slope also shows a gradually increasing trend. Due to the relatively small drag coefficient and relatively large lift coefficient under the condition of a change in attack angle of 0.8 ° per second, there is the highest lift to drag ratio among the three operating conditions. Although there is a significant lift coefficient with an attack angle change of 8 ° per second, the drag coefficient is also the largest among the three operating conditions, which affects the magnitude of the lift to drag ratio.



(a) Comparison figure of lift coefficient



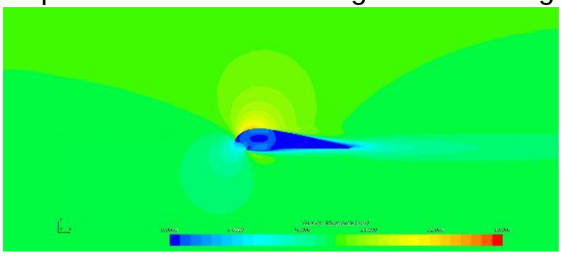
(b) Comparison figure of drag coefficient



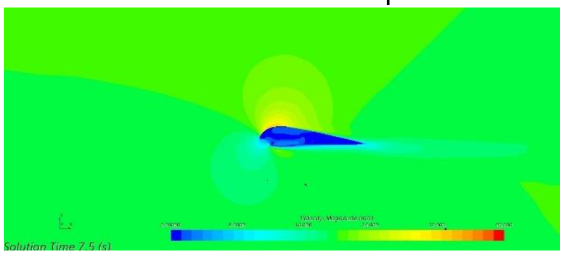
(c) Comparison figure of lift and drag coefficient

Figure 6- Steady and unsteady comparative figure of oversize modular parafoilr.

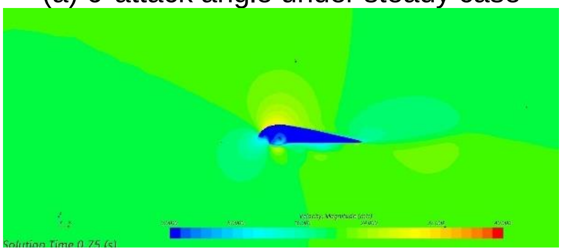
The velocity contour for selecting 6 °, 8 °, and 10 ° attack angles is shown in Figure 7. Further study the impact of continuous changes in incoming wind direction on the movement of parafoil.



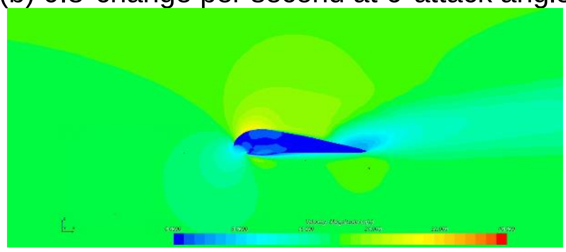
(a) 6°attack angle under steady case



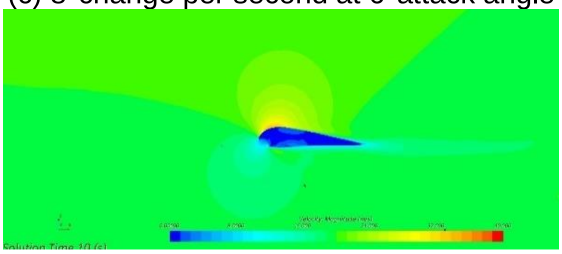
(b) 0.8°change per second at 6°attack angle



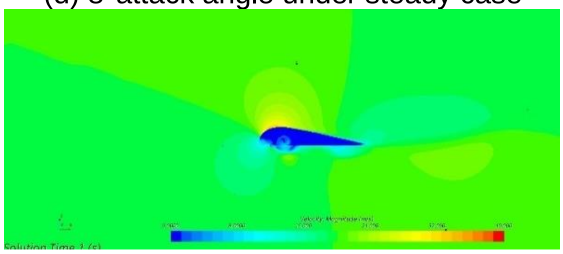
(c) 8°change per second at 6°attack angle



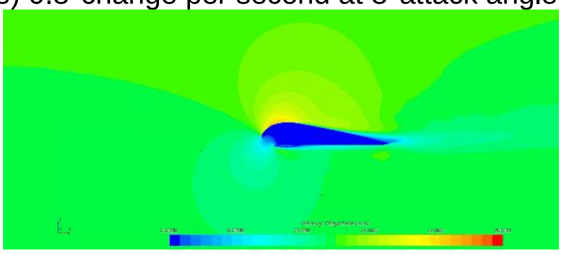
(d) 8°attack angle under steady case



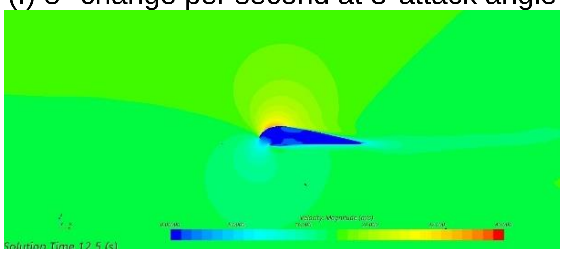
(e) 0.8°change per second at 8°attack angle



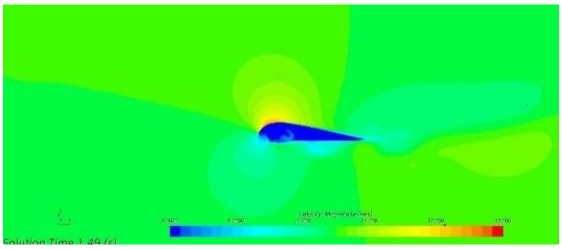
(f) 8° change per second at 8°attack angle



(g) 10°attack angle under steady case



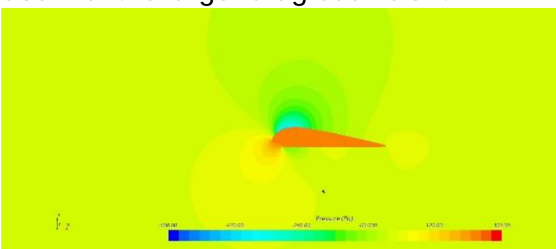
(h) 0.8°change per second at 10°attack angle



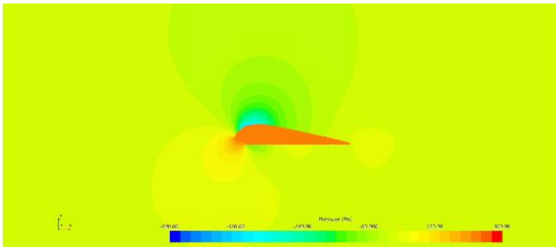
(i) 8°change per second at 10°attack angle

Figure 7-Steady and unsteady comparative velocity contour of oversize modular parafoilr

The difference in velocity contour of oversize modular parafoil under different wind directions at the same angle of attack has the same pattern, which is similar to that of small paragliders. At the incision, the steady low-speed zone has a larger area and slower velocity changes. There is a smaller low-speed zone when the angle of attack varies by 8° per second. On the lower wing surface, the faster the wind direction changes, the larger the low-speed zone is, resulting in an increase in pressure on the lower wing surface. When the wind direction changes to an angle of attack of 8 ° per second, the high-speed zone velocity at the leading edge of the upper wing surface is maximal. And the range of maximum speed is the largest among the three working conditions. It reduces the pressure on the upper wing surface under this operating condition. Overall, the change in attack angle of 0.8 ° per second is similar to the velocity distribution at steady state. Therefore, the two operating conditions have similar aerodynamic coefficients. The resistance coefficient is mainly composed of induced resistance, pressure difference resistance, and frictional resistance. The friction coefficient of the same parachute is the same. And the friction resistance of the three working conditions remains consistent. But due to the faster changes in wind direction, the low-speed zone at the parachute incision is more concentrated. There is a larger high-speed area at the trailing edge. A significant pressure difference is formed before and after, and increases pressure resistance of the paraglider. And due to the increase in lift, the induced drag increases more significantly, which is an important reason for the larger drag coefficient.

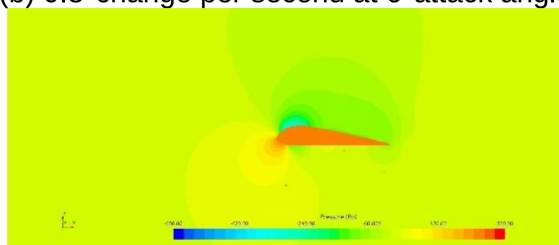


(a) 6°attack angle under steady case

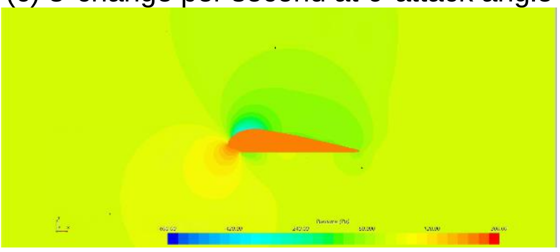


(b) 0.8°change per second at 6°attack angle

(c) 8°change per second at 6°attack angle

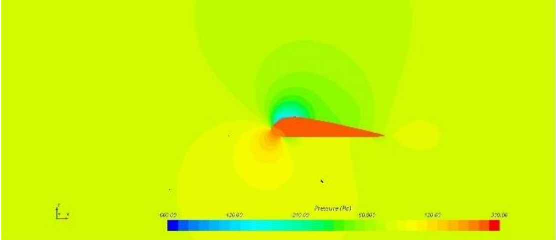


(d) 8°attack angle under steady case

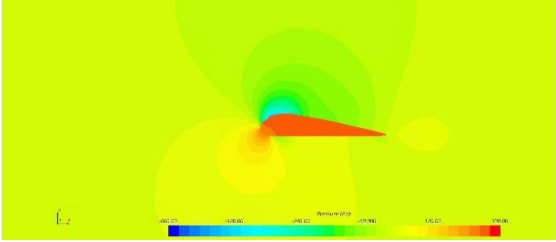


(e) 0.8°change per second at 8°attack angle

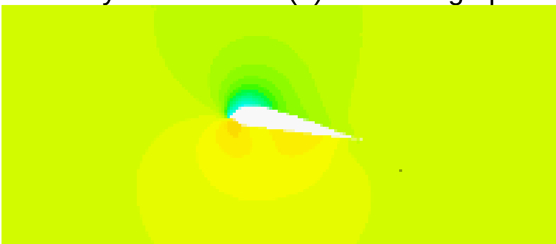
(f) 8° change per second at 8°attack angle



(g) 10°attack angle under steady case



(h) 0.8°change per second at 10°attack angle



(i) 8°change per second at 10°attack angle

Figure 8-Steady and unsteady comparative pressure contour of oversize modular parafoilr

The pressure contour of a super large combined paraglider under different wind direction changes is shown in Figure 8. The overall change pattern is similar to that of a small paraglider. Under the condition of a change in attack angle of 0.8 ° per second, the pressure cloud map distribution is very similar to the pressure cloud map distribution at steady state. It can be considered that the pressure distribution in the flow field around the parachute is basically the same as that at a constant angle of attack. When the wind direction changes to 8 ° angle of attack per second, there is a significant difference in the pressure distribution of the flow field around the parachute. Near the leading edge incision, the faster the wind direction changes, the greater the maximum pressure under the working condition is. In the low-pressure area of the leading edge upper wing, there is also a phenomenon where the minimum pressure decreases as the wind direction changes faster. Under the condition of wind direction reaching 8 ° angle of attack per second, the range of high-pressure area on the wing surface under the umbrella increases. And new high-pressure zones will appear near the trailing edge, greatly increasing the pressure difference between the upper and lower surfaces of the parachute. This is the reason for the high lift coefficient in this operating condition. Due to the high lift coefficient, the induced drag under the condition of an 8 ° angle of attack change per second will also increase. There is also a significant increase in the resistance coefficient under this working condition

4. Conclusion

This article uses commercial software to define UDF functions to control changes in flow direction, and studies the possible impact of sudden changes in wind direction on the aerodynamic performance of paragliders. This article sets the wind speed to remain constant, changes the wind direction from 0 ° angle of attack to 12 ° angle of attack, selects the range of attack angles from 4 ° to 12 ° after stable convergence as the region of attack angle variation. This article studies the 836m^2 oversize modular parafoil under different attack angle and velocity changes. The aerodynamic performance changes of the paraglider when the 8 ° angle of attack changes are completed in 10 seconds, 1 second, and 0.1 second, respectively. Major findings are summarized as follows:

1)The difference between the results of the oversize modular parafoil and a steady one is not significant when the angle of attack changes slowly. The distribution of the flow field is extremely similar. Therefore, there is not much difference in aerodynamic coefficients, and the aerodynamic performance is very similar. It can be considered that the oversize modular parafoil is not affected by any changes in attack angle of 0.8 ° per second.

2) The aerodynamic performance of the oversize modular parafoil is significantly affected when the wind direction changes to 8 ° angle of attack per second. The lift resistance has significant increase. This is because the faster change in wind direction changes the pressure distribution and flow field around the parachute. The pressure difference between the upper and lower wing surfaces of the parachute increases. It results in changes in aerodynamic coefficients.

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6. Copyright Statement

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