STRUCTURAL DESIGN AND ANALYSIS OF A QUADROTOR FIXED-WING HYBRID UAV WING

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Abstract

In this paper, we mainly focus on the wing structure design and analysis progress of a Quadrotor Fixed-wing Hybrid UAV. This paper starts with a brief introduction of the Quadrotor Fixed-wing Hybrid UAV. Then we bring up our own layout of the UAV. The following up part defines the most severe load situations that need to be considered during design and analysis progress. Based on these research, we come up with a wing structure design solution using girder structure with sandwich skin. And the following analysis shows that it can effectively bear the static loads produced during the flight. Based on this layout of wing structure, we carried out ply optimization for the structural components, which achieves further weight reduction.

1 Introduction

Recently, there has been a rapid development in design and manufacture of unmanned aerial vehicle(UAV). And UAVs have been deployed in missions including mapping, surveillance, aerial photography, cargo transportation, etc. Currently, there are mainly two types of commercial UAVs, which include the Fixed-wing UAV and the Multi-rotor UAV. For Fixed-wing UAV, it has great cruising ability and operating radius. However, it relies on runway to perform takeoff and landing, which restricts the usage of Fixed-wing UAV in severe environments. As for Multi-rotor UAV, it has the ability of vertical takeoff and landing(VTOL) and hovering over target point. But the limited cruising speed and operating radius restricts its usage in long time cruising or long distance cruising missions. With the expansion of usage of UAVs in different areas, it becomes a demanding request to develop UAVs that are great in performance, easy to operate, and able to perform different missions.

The Quadrotor Fixed-wing Hybrid UAV combines the layout of the Fixed-wing UAV and the Multi-rotor UAV, which allows it to take-off and land vertically and cruise with high speed and great efficiency. Thus it has both the advantages of Fixed-wing UAVs and Multi-rotor UAVs, which makes it possible to deploy this kind of UAV in aerial photography, cargo transportation, reconnaissance, patrol, and so on. Compare with other kinds of UAV, the Quadrotor Fixed-wing Hybrid UAV has advantages in low requirement for runway, great implementability, simplicity in systems design, production and manufacture. And there has been a significant interest in the Quadrotor Fixed-wing Hybrid UAV in recent years.

Currently, there has been several related research conducted about this topic. During the research, the technical characteristics of different types of Fixed-wing VTOL UAV and a feasible design plan of hybrid quadrotor UAV is put forward [1]. Also, a prototype of a Fixed-wing UAV with multi rotor control system is developed, which pretends increase flight time of multi rotor system using aerodynamic characteristics [2]. And the steady state and transient models of fuel cells and batteries is developed and validated experimentally [3]. Furthermore, an UAV with level flight, VTOL, and mode-changing capability is analysed and modelled [4]. Besides, the control scheme and control system are considered for VTOL UAVs with level flight capability [5, 6].

This paper focuses on the structural design and analysis of the wing structure of a Quadrotor

Fixed-wing Hybrid UAV considering the severest load conditions in vertical take-off and landing and cruising. In subsequent sections of the paper, we describe the wing geometry and structural layout, the static loading condition, and intensity analysis. Moreover, a ply optimization progress for the wing structure components is discussed.

2 Layout and load situation definition

2.1 Layout of the UAV

This quadrotor fixed-wing hybrid UAV is designed to satisfy the need for carrying out different missions in landforms not suitable for running take-off and landing, which is a long cruising endurance UAV with vertical take-off and landing ability. In this paper, a Quadrotor Fixed-wing Hybrid UAV is brought up, which is designed for rural areas with poor traffic. Based on the design solution of this UAV, it can be used as a common platform for different missions including cargo transportation, patrolling, surveillance, and so on. To achieve this goal, this UAV is design in a modularization way, which allows it to be modified easily to satisfy the different requests of different missions. For example, the cargo at the belly can be easily replaced with different modules, including optronics pod, cargo pod, fuel tank and so on. Taking all these requests in to consideration, the final design solution is a 60kg UAV, with a 14.5kg payload including fuel.

Figure 1 shows the layout of this UAV. It's a fixed wing, single tail boom aircraft with additional quadrotor. The aircraft is manufactured using composite materials throughout most of the structure components. During the design of composite structures, the primary requirement is that the structures must be able to bear the loads during flight. Besides that, we need to combine formed experiences and take consideration of lightweight structure design, manufacture technique, production quality control, and so on to form the final structure design solution.

Fig.1 Layout of the UAV

The Quadrotor Fixed-wing Hybrid UAV combined the characteristics of both Fixed-wing UAV and Multi-rotor UAV. The quadrotors are installed under the wing to provide the lift for hovering in quadrotor mode. In this mode, the lift and moment produced by rotors will all be transmitted to the fuselage through wing structure. Especially, to control the posture of the UAV, rotor system could generate great moment, which requires great torsional capacity from the wing structure. Thus the inner part of the wing is rectangular wing, which has relatively better structure height, and is in favor of structure torsional capacity. However, in fixed-wing mode, trapezoidal wing has lower induced drag than the rectangular wing, which increase the cruising efficiency. Thus, the wing shape is design as Figure 2. The inner part is rectangular wing, and the outer part is trapezoidal wing. And the wing span is 4.9m.

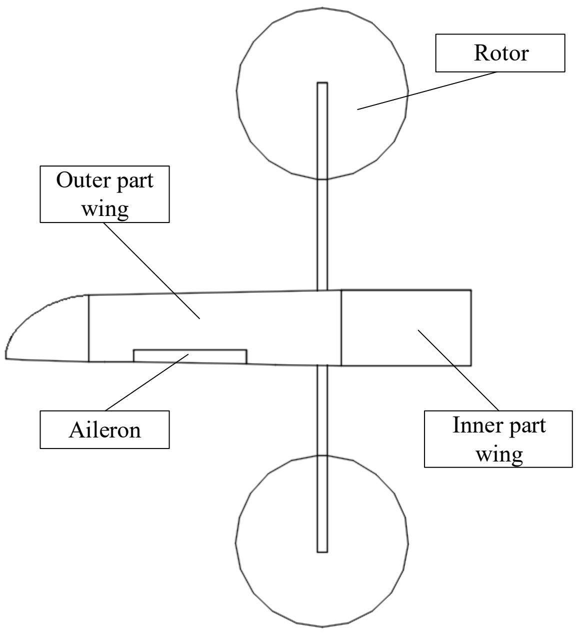


Fig.2 Layout of the UAV wing

2.2 Load situation definition

For the quadrotor fixed-wing hybrid UAV, it can hover in two different modes: fixed-wing mode and quadrotor mode. In fixed-wing mode, it's lifted by aerodynamic forces, which is in consistent with general fixed-wing aircraft. However, in quadrotor mode, it's lifted and controlled by rotors. Thus load conditions and load factors should be analysis in two modes separately.

In fixed-wing mode, the design load factor is chosen to be +3.8 to -1.5, with a combined factor of safety of 1.5. In contrary, load in quadrotor mode is generated by rotors and aerodynamics. In quadrotor mode, the UAV id designed to be able to resistant wind from heading direction at 15m/s. Besides that, the four rotors can generate 120kg lift in total. In this situation, the load factor $n_{y,\max}$ can be calculated as equation 1.

$$n_{y,\max} = \frac{Y_0 + \Delta Y}{G} = \frac{Y_0 + 0.5\rho_H v_w^2 S c_y^\alpha}{G} c_y^\alpha \quad (1)$$

In equation 1, $n_{y,\max}$ is the load factor;

Y_0 is the lift generated by the rotors;

ΔY is the additional lift generated by the wind;

G is the weight of the UAV;

ρ_H is the density of air at sea level, which is $1.29 kg/m^3$;

v_w is the wind speed;

S is the area of wing, which is $1.81 m^2$;

c_y^α is the lift coefficient of this UAV, which is 1.5.

Combined together, the max load factor in quadrotor mode is 2.65.

However, according to former test flight, there is a circumstance that wing shows a significant twist during vertical take-off and landing in crosswind condition. Crosswind would cause a yaw moment, which almost equals the control moment can be supplied by rotors. This may induce two rotors on the opposite corners work at full revolving speed and others stops working, forming a twisting moment around pitching axle of wing.

Thus, we need take these three situations in condition during the design and analysis of wing structure of this UAV:

- Situation 1: the UAV bears a load factor of 3.8 in fixed-wing mode;
- Situation 2: all the rotors work at full revolving speed and the UAV bears a heading wind at 15m/s in quadrotor mode;
- Situation 3: two rotors on the opposite corners work at full revolving speed and others stops working in quadrotor mode.

3 Wing structure design solution

Wing-box structure is one of the most common structure in aircrafts. There mainly three types of composite wing-box structures, including girder structure with thin skin, multi-spar structure, and full height sandwich structure. The multi-spar structure is formed with thick skin and multiple spars. It has great bending stiffness and torsional rigidity, which makes it more suitable for high speed UAVs. The full height sandwich structure is a unibody structure formed with composite skin and foam core, usually used in thin airfoil structure and wedge-shaped structures. The girder structure is a frame structure formed with spars, ribs, and several stringers. For small size UAVs, the girder wing structure frame can use only spars and ribs when the skin is sandwich skin. For the UAV discussed in this paper, it is a small size UAV, and the circuity of rotor systems and control modules of rotor system and control surfaces are arranged in the internal space of the wing. Thus the we choose girder structure with sandwich skin for the main part of the wing, and full height sandwich structure for control surfaces and trailing edge areas.

In fixed-wing mode, the wing load is mainly aerodynamic loads. The aerodynamic load distributes upon the skin and transmits to the spars and ribs. Finally, the load transmits to the fuselage in shear internal force and bending internal force. The webs of the spars are parallel with the shear internal force. Thus most shear internal force is transmitted through the webs. As for bending internal force, it transmitted mainly through the caps of the spars. In quadrotor mode, the rotor system provides the lift and control moment for the UAV. In this mode, lift transmits in the same way as in fixed-wing mode. But for moments, they will be transmitted by closed cells formed by spars and skins. During the design

phase, we need to pay more attention on the closed cell in order to improve the torsional capacity of the wing structure.
As shown in figure 3, the wing primary structure includes two spars located at 15% and 60% chord, three ribs, upper and lower sandwich skins. And the rotor system is connected with the middle spar, so that the lift and moment produced by the rotor system can be transmitted via the wing structure.

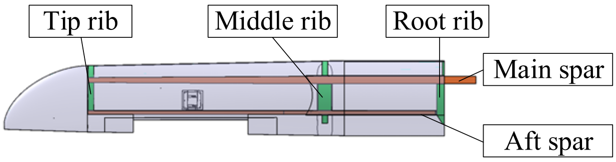
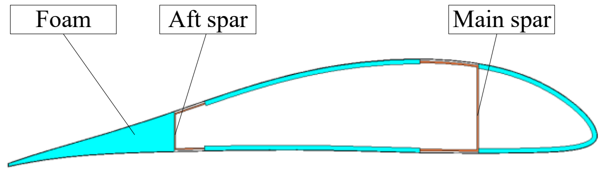
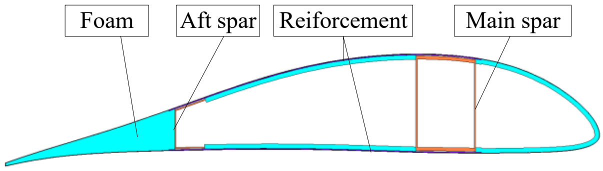


Fig.3 Wing structure layout

For the outer part of the wing structure, it mainly bears the aerodynamic load generated during fixed-wing mode. The cross section of outer part wing structure is shown as figure 4(a). The main spar and the aft spar are both channel beam. And the spars are made out of carbon-fiber woven prepreg fabric. And the skin uses sandwich construction with low-density foam core and carbon-fiber woven prepreg fabric, which would effectively increase the rigidity of skin. Considering that the inner part wing structure has to provide the torsional capacity to bear the moments produced by quadrotor system in additional to aerodynamic loads, the main spar of inner part wing structure uses rectangular cross section instead. Besides that, the skin between main bar and aft bar are reinforced to increase the torsional rigidity of inner part wing structure as shown in figure 4(b). Thus, the main spar, the aft spar and skins form two closed cell providing wing torsional capacity. Also, the main spar has a rectangular cross section extends inside fuselage forming a carry-through structure. It balances the main part of bending loads. And shear load is transferred through the carry-through structure and pin connecting between root rib and fuselage.



(a)Cross section of outer part wing structure



(b)Cross section of inner part wing structure
Fig.4 Cross sections of wing structure

As mentioned in former parts, the skin uses sandwich construction. But in areas where skin is glued with spars or ribs, the form core needs to be removed in case the form might be ripped off under severe load. Also, a transition area is designed as shown in figure 5 between normal skin and reinforced skin to avoid stress concentration caused by thickness change.

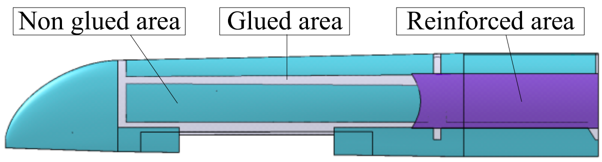


Fig.5 Skin zoning

4 Intensity analysis and discussion

4.1 Intensity analysis

After we decided the load situations we need to consider and the wing structure design solution, we set up a finite element model as shown in figure 6 to analyse the static strength of the wing structure.

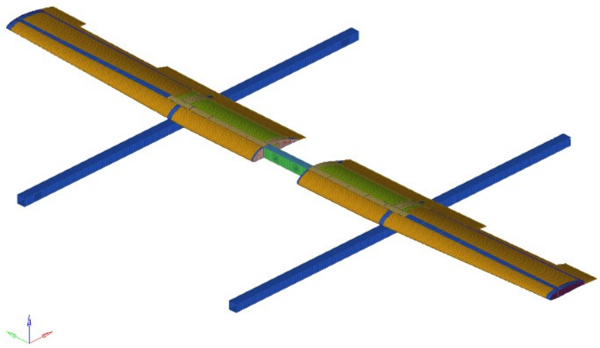
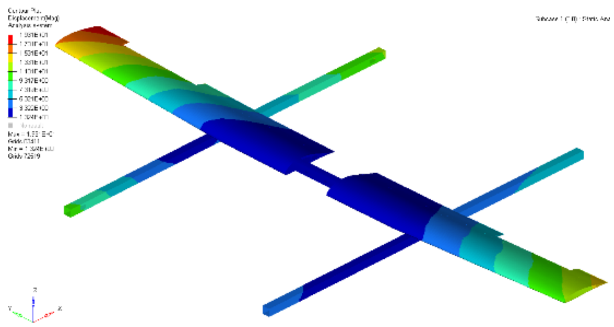


Fig.6 Finite Element Model for static strength analysis

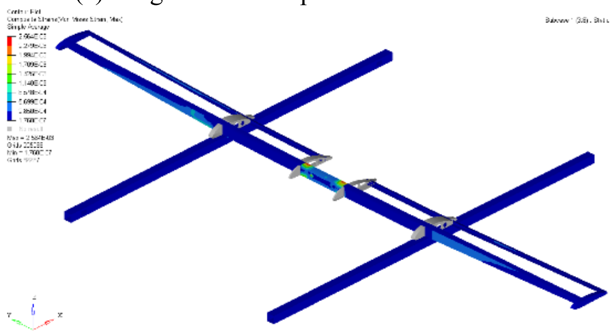
The displacement, stress, and strain distribution in different load situations are given in the following part. In situation 1, the wing tip displacement is 19.31mm. The maximum strain is 2564με, and the maximum stress is 463.6MPa. According to the analysis results, the strain level of outer part wing is higher than the inner part wing. This is in coordination with the wing structure design solution. The inner part wing structure is reinforced to increase the torsional capacity, and the reinforcement also increases the bending and shear capacity. And the outer part wing structure is designed for bearing the aerodynamic load generated during cruising, which contributes to efficiency improvement and structural weight control. Also most of the load is transmitted to fuselage via main spar due to its higher strength, which leads to the high strain level in the root part of main spar.

In situation 2, the wing tip displacement is 6.04mm, and the maximum displacement of mounting point of rotors is 45.86mm. The maximum strain is 1992με, and the maximum stress is 349.0MPa. Compared with situation 1, the load in this situation is much lower, thus the strain and stress level is relatively lower.

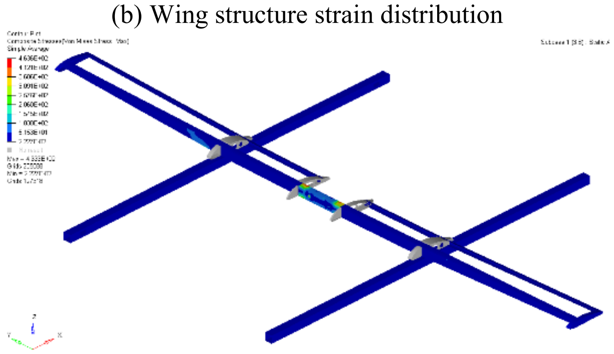
In situation 3, the wing tip displacement is 8.87mm, and the maximum displacement of mounting point of rotors is 83.69mm. The maximum strain is 2747με, and the maximum stress is 400.8MPa. According to the analysis results, the closed cells formed by spars and skins all involved in bearing the moment produced by rotor system. The results of steady-state strength analysis in the situations we chosen shows that the wing structure design solution can effectively bear the load produced during the flight.



(a)Wing structure displacement distribution

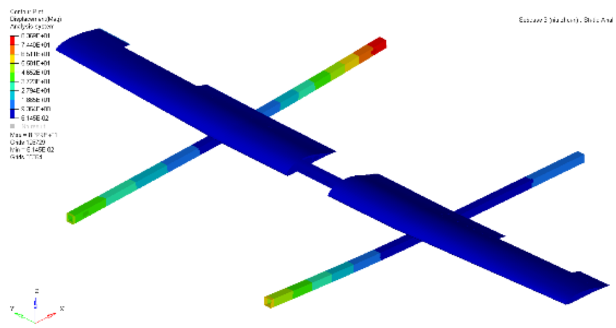


(b) Wing structure strain distribution

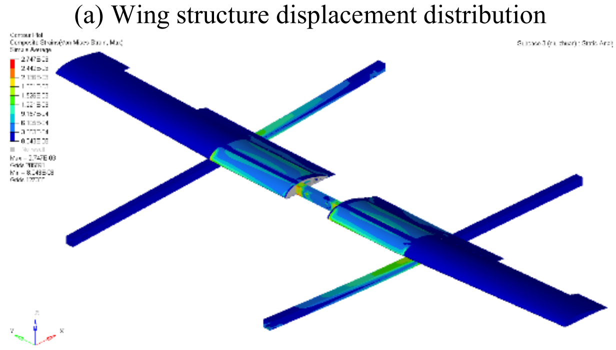


(c) Wing structure stress distribution

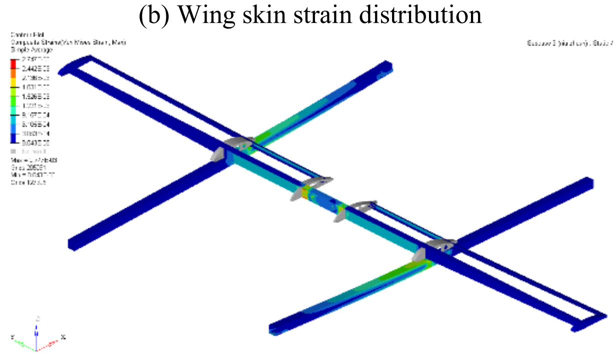
Fig.7 Static strength analysis results in situation 1



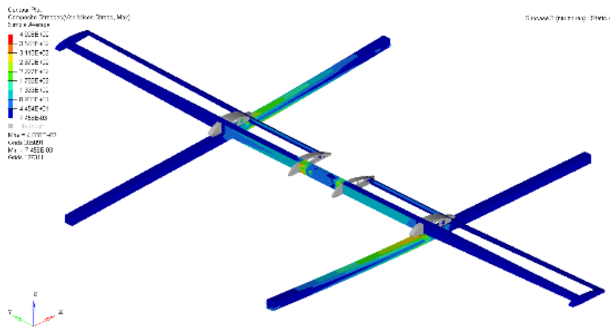
(a) Wing structure displacement distribution



(b) Wing skin strain distribution



(c) Wing structure strain distribution



(d) Wing structure stress distribution

Fig.8 Static strength analysis results in situation 3

4.2 Composite structure ply optimization

In the former part of this paper we defined the wing structure layout. Based on this, we set up a simplified finite element model for ply optimization for the wing spars and skins as shown in figure 9.

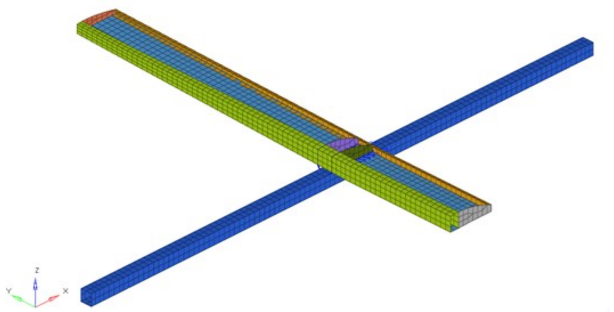


Fig.9 Simplified wing structure finite element model

The optimization progress includes free-size optimization, size optimization, and shuffling optimization. In this progress, the restriction is that the composite strain and stress are not allowed to exceed the allowable values. Also, production restrictions are taken into considering, including the thickness of single ply and the maximum repetition times of a single direction ply. And the optimization object is the lightest weight of wing structure.

After this optimization progress, the thickness distribution of wing spars and skins are shown as figure 10. We can see that the thickness of spars and skins gradually become thicked from wing tip to the root.

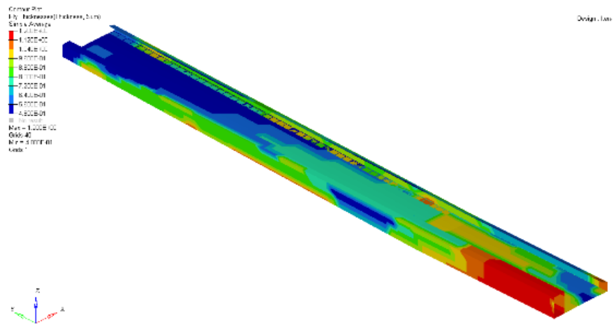
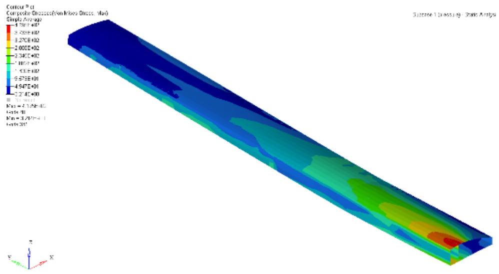
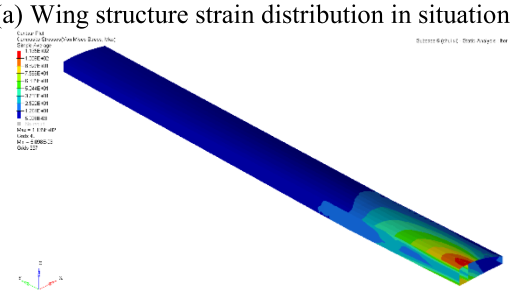


Fig.10 Thickness distribution after optimization

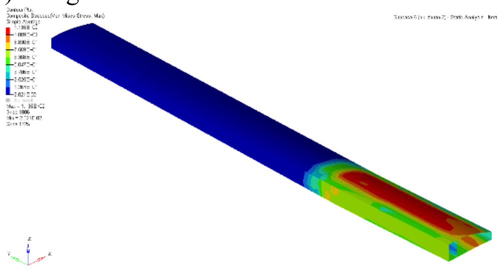
The wing structure strain distribution after optimization is shown in figure 11. It can be seen that in situation 1 and situation 2, the strain gradually increases from wing tip to the root. And the stress concentration area is the root area of main spar. As for situation 3, the whole closed cell form by spars and skins of inner part wing is at high strain level, which means that the whole cell effectively involved in providing the torsional capacity required to bear the load.



(a) Wing structure strain distribution in situation 1



(b) Wing structure strain distribution in situation 2



(c) Wing structure strain distribution in situation 3

Fig.11 Wing structure strain distribution after optimization

Compare with the wing structure before the optimization, the weight of wing spars and skins in this simplified wing structure changes from 1.244kg to 1.060kg. Besides that, the structure strain level is closer to the allowable value. Thus, the optimization progress brings up a ply solution that exercises the designability and structural-load-carrying capacity of the composite materials, which improves the efficiency and weight reduction of wing structure.

5 conclusion

In this paper, an overview of structural design and analysis progress of a composite wing for a quadrotor fixed-wing hybrid UAV was presented. According to the design of the UAV, the most severe load situations are the UAV bearing the maximum design load factor in fixed-wing mode and quadrotor mode, and two rotors on the opposite corners working at full revolving speed causing a twisting moment around pitching axle of wing. Based on these situations, a wing structure design solution using girder structure with sandwich skin is brought up. And a finite element model of the wing was developed to analyse the displacement, strain, and stress of wing structure during flight. According to the analysis results, the design solution can provide sufficient static strength in these situations. And with the ply optimization progress of wing structure components, we manage to achieve further weight reduction without affecting the wing structure strength. As part of future efforts, dynamic analysis will be performed to investigate how the structure design solution performs during flight.

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