

Research Article

Flight Endurance Increasing Technology of New Energy UAV Based on a Strut-Braced Wing

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Received 11 August 2022; Revised 30 August 2022; Accepted 31 August 2022; Published 5 October 2022

Academic Editor: Xingling Shao

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This paper explores the feasibility of using the strut-braced wing (SBW) configuration to improve the flight endurance of the new energy unmanned aerial vehicle (UAV). A conceptual scheme of a new energy UAV with SBW configuration was designed, and the influence of the SBW on the aerodynamic and structural performance was analyzed. The results show that the SBW can improve the structural performance of the wing and increase the solar laying area of the wing, but the aerodynamic performance did not improve significantly. From the perspective of UAV energy consumption in level flight, the subtraction between electric output power and solar input power is selected as the evaluation index of the increasing effect of the flight endurance. A multidisciplinary design optimization (MDO) model was established considering the coupling of aerodynamics, structure, energy, and weight. Surrogate model technology and multiobjective genetic algorithm are used to optimize the SBW configuration. Compared with the conventional configuration, the optimal design result of the SBW configuration can reduce the level-flight output power and increase the solar input power, thus effectively increasing the flight endurance of the UAV.

1. Introduction

With the advantages of green and environmental protection, new energy UAVs are becoming a research hotspot. The long-endurance performance of new energy UAVs is its goal and the basis for its wide application. New energy UAV mainly includes lithium battery UAVs, solar UAVs, hydrogen UAVs, and solar/hydrogen hybrid energy UAVs. The *AtlantikSolar*, a solar UAV developed by the Autonomous Systems Lab at eth Zurich in Switzerland, has verified the ability of a small solar-powered UAV to fly long endurance in low-altitude and windy conditions, and has maintained a long endurance flight record of 81 h [1, 2]. The *Ion Tiger*, a hydrogen UAV developed by the U.S. Naval Research Laboratory, successfully flew with liquid hydrogen for 48 hours, setting an endurance record for a small-hydrogen fuel cell UAV [3]. For low-altitude and small-new energy UAVs, energy characteristics are the main factor determining the long-endurance capability of UAVs and are also deeply coupled with the conceptual design of UAVs. The solar/hydrogen hybrid energy UAV can take advantage of different energy sources. The *EAV-2*, a solar/hydrogen hybrid energy UAV developed

by the Korea Aerospace Research Institute (KARI), successfully flew for 22 h in 2012 [4, 5]. From 2018, the U.S. Naval Research Laboratory carried out research work on the *Hybrid Tiger* solar/fuel cell/soaring UAV [6].

However, the energy density of lithium batteries is still low, the efficiency of solar cells is greatly affected by the weather, and the hydrogen fuel cells and storage devices increase the weight of UAVs. For new energy UAVs using solar energy, the increase in the wing area can lay more solar cells and provide more solar input energy. But the increase of the wing area will affect the weight and aerodynamic characteristics of the UAV and also put forward new requirements for the design of structure. Selecting the appropriate design scheme of the wing structure and satisfying the constraints of structural strength, weight, and aerodynamic characteristics will increase the wing area and the laying area of solar cells, which is one of the technical ways to improve the flight endurance of new energy UAVs.

In the 1950s, researchers proposed the idea of using truss-braced wing (TBW) configuration in transport planes and explored the advantages of the TBW in takeoff weight of high-aspect ratio aircraft [7]. The strut-braced wing

(SBW) configuration can be considered as the most basic representation of the TBW topology [8]. Because the strut and pylon bear part of the load, the SBW can reduce the bending moment of the main wing, which is beneficial to increasing the aspect ratio and wing area [9]. The larger aspect ratio can not only increase lift but also reduce induced drag, thus improving the aerodynamic performance of the aircraft [10, 11]. Since the 21st century, the multidisciplinary design optimization (MDO) method has been widely applied to the conceptual design of the passenger plane with TBW configuration [12]. Scholars have studied the advantages of the SBW configuration in terms of takeoff weight, fuel consumption, and lift-drag ratio by using the MDO method [13, 14]. Boeing proposed the “SUGAR” program (Subsonic Super Green Aircraft Research Program), which explored the feasibility of using TBW configuration as a subsonic aircraft wing scheme, and the hybrid power system modeling, energy cost estimation, and acoustic analysis for this configuration have been studied [15]. Chau and Zingg optimized the aerodynamic shape of SBW based on the Reynolds-averaged N-S equation, mitigating shock waves, boundary layer separation, and other flow disturbance effects [16]. The SBW configuration has shown significant advantages over conventional configuration in the research of passenger aircraft.

In this paper, the application of SBW configuration to the design of low-altitude small solar/hydrogen hybrid energy UAVs is proposed to improve flight endurance. The innovations of this paper are that a conceptual scheme of a new energy UAV with SBW configuration is proposed, and the SBW configuration is optimized by the MDO model. The contribution of this paper is to analyze the aerodynamic and structural performance of different design parameters and further obtain optimal design results through the MDO model. The main challenge of this paper is how to put forward an appropriate indicator of the MDO model for describing the flight endurance of a new energy UAV with SBW configuration.

The rest of this paper is organized as follows: The conceptual design of the UAV is described in Section 2, including the basic information of the prototype and the configuration scheme of a hybrid energy UAV with SBW configuration. Section 3 discusses the effects of SBW parameters on aerodynamic and structural performance containing computational fluid dynamics (CFD) and finite element analysis (FEA) results of different design parameters. Section 4 proposes the evaluation index of the flight endurance and establishes the aerodynamic-, structure-, energy-, and weight-coupled MDO model including analysis methods of each discipline. Section 5 presents the MDO results and associated discussion about the schemes of the prototype and SBW configuration. Finally, the conclusions are made in Section 6.

2. Conceptual Design of the UAV

2.1. Mission Profile and Design Parameters of the Prototype. The mission profile of the prototype is shown in Figure 1(a), the configuration of the prototype is shown in Figure 1(b), and aerodynamic shape parameters are shown in Table 1.

2.2. Configuration Scheme Design. The TBW configuration can be divided into three types by topological method, as shown in Figure 2.

Previous studies on passenger aircraft and transport aircraft mainly use the SBW and 1-jury TBW to reduce energy consumption and takeoff weight. The results show that the performance of SBW is better than the 1-jury TBW [17, 18]. After liberating the constraints on the wingspan, the researchers found that 1-jury TBW was significantly better than SBW in terms of fuel consumption and structural performance. There was no significant difference between the 1-jury TBW and 2-jury TBW [18]. Compared with the SBW and 1-jury TBW, the multijury TBW can achieve a larger aspect ratio [19]. However, the multijury TBW comes with a cost in takeoff weight. As the number of juries increases, so does the takeoff weight [20].

In general, the SBW configuration can increase the strength and stiffness of the wing with little impact on weight increase. For small UAVs, it is easier to design and implement. Therefore, this paper proposes a prototype-based hybrid energy UAV with an SBW configuration schematic design (as shown in Figure 3).

3. Design Parameters of the SBW

3.1. Selection of Aerodynamic Design Parameters. In order to study the endurance-increasing effect of the SBW, the parameters of fuselage, tail, and other components in this scheme are consistent with the prototype. The main aerodynamic design parameters are shown in Table 2. The SBW configuration is shown in Figure 4.

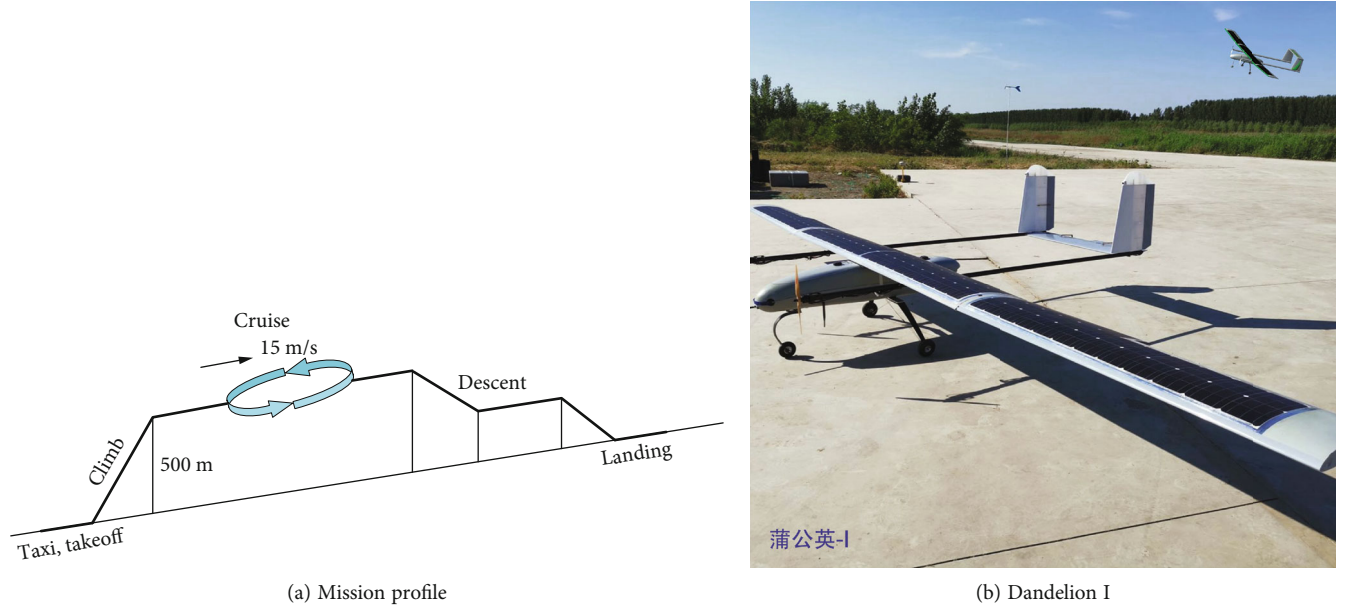
In order to design the SBW efficiently, it is necessary to select the design parameters as variable or constant in the later design. The principle of selection is to fully consider the influence of parameters on the aerodynamic, structural, weight, and other performances of the wing and consider the constraints of laying solar cells.

3.1.1. Design Parameters of the Wing. For C_{wing} , solar cells are laid on the upper surface of the wing. If the chord length of the wing is changed, the solar cell laying scheme needs to be redesigned, which increases the complexity of the UAV design. Therefore, the chord length of the wing is selected as a constant.

For L_{wing} , the wing is the main component of generating lift and the wingspan has a great influence on the aerodynamic and structural performance of the UAV. Solar cells are easy to lay along the direction of the wingspan, so there is no need to redesign the laying scheme. Thus, the wingspan is selected as a design variable.

In order to study the influence of the wingspan on the aerodynamic performance of the UAV with support SBW, C_{strut} is fixed, $L_{strut} = L_{wing}/2$, and the wingspan is the only variable. The computational fluid dynamics (CFD) method is used to calculate aerodynamic performance. Using the CFD analysis results of the conventional wing as a baseline, the comparison results are shown in Figure 5.

Compared with the conventional configuration, lift coefficient and drag coefficient increase with the strut and pylon.

FIGURE 1: Mission profile and configuration of *Dandelion I*.TABLE 1: Aerodynamic shape parameters of *Dandelion I*.

Major component	Parameter name	Value and unit
Wing	Wingspan	6150 mm
	Wing chord	423 mm
	Install angle	2.5°
	Dihedral angle	3°
	Sweep angle	0°
	Root-tip ratio	1
Tail	Horizontal tail span	1260 mm
	Horizontal tail chord	253 mm
	Horizontal tail root-tip ratio	1
Fuselage	Vertical tail span	450 mm
	Vertical tail cord	260 mm
	Cross-section height	250 mm
	Cross-section width	250 mm
	Length	1342.96 mm

The increase in drag coefficient is larger, so the lift-drag ratio of SBW is lower than conventional configuration. Without the changing chord of the strut and pylon, the increment of aerodynamic coefficient does not change randomly with the increase of the wingspan.

3.1.2. Relative Position of the Strut, Pylon, and Wing. For ξ_{strut} , in order to ensure the performance of the structure and reduce the weight, the strut and pylon spar is directly connected to the wing spar. So, the chordwise position of the strut and pylon is determined by the position of the wing spar.

For H_{strut} , the distance between the wing and the root of the strut is decided by the cross-section of fuselage.

For L_{strut} , the spanwise position of the strut has great influence on the structure weight. The aerodynamic perfor-

mance of the strut and pylon will also affect the aerodynamic performance of UAV. The CFD method is used for analyzing the influence of L_{strut} about aerodynamic performance. Some design parameters are fixed, $L_{wing} = 3.4m$, $C_{strut} = 50 mm$, and L_{strut} is the only variable. Similarly, the conventional wing with the same wingspan is used as a baseline and comparative results are shown in Figure 6.

With the increase of L_{strut} , lift coefficient and drag coefficient increase simultaneously and the increment of drag coefficient is larger, so the lift-drag ratio decreases accordingly. Without changing the design parameters of the wing, the aerodynamic performance of the SBW is lower than that of the conventional one due to the existence of the strut and pylon. As the spanwise position of the pylon increases, the affected area on the lower surface of the main wing increases, resulting in a decrease of the lift-to-drag ratio. From the perspective of aerodynamic performance, the spanwise position of the pylon should be reduced as much as possible, which means that under the condition of the same wingspan, the aerodynamic performance of the conventional UAV is better than the SBW.

3.1.3. Design Parameters of the Strut and Pylon

(1) *Distance between the Wing and the Root of the Strut.* This distance is the height of the fuselage.

For H_{pylon} , if the length of the pylon is too long, greater frictional drag and additional weight will be generated; if the length is too short, the distance between strut and wing will be too close, which will interfere in the aerodynamic performance between the wing and the strut. So, H_{pylon} should be designed as a suitable constant.

For C_{strut} , the design of the strut and pylon should meet the requirements of aerodynamic performance, strength, and stiffness. The influences of C_{strut} on the aerodynamic

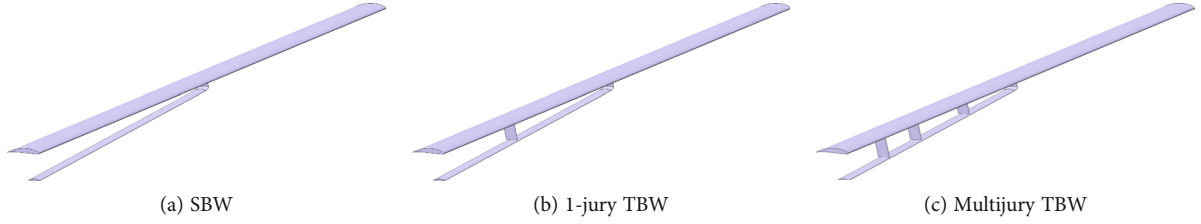


FIGURE 2: Different TBW configuration.

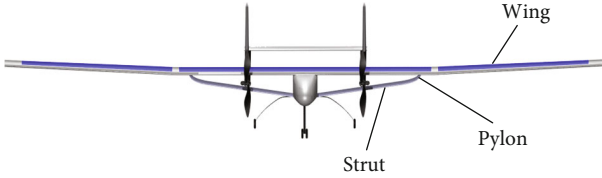


FIGURE 3: Hybrid energy UAV with SBW configuration.

TABLE 2: Aerodynamic design parameters.

Number	Name
1	Wingspan, $2L_{\text{wing}}$
2	Wing chord, C_{wing}
3	Chord of strut and pylon, C_{strut}
4	Chordwise position of strut, ξ_{strut}
5	Distance between wing and root of strut, H_{strut}
6	Length of pylon, H_{pylon}
7	Spanwise position of strut, L_{strut}

performance of the wing were studied. L_{wing} , L_{strut} , and other design parameters are fixed, only C_{strut} changed for CFD analysis. The baseline is a conventional wing with the same wingspan. The comparative results are shown in Figure 7.

It can be seen that the strut and pylon can provide additional lift for the UAV but also increase the drag. The increase of the chord length of the strut and pylon reduces the lift-drag ratio, which adversely affects the aerodynamic performance of the UAV. When the design parameters of the wing and the relative position of the strut and pylon are not changed, the increase of the chord of strut and pylon will have adverse effects on the aerodynamic performance. With the increase of the strut chord, the projection area of the strut on the lower surface of the wing also increases. The pressure distribution of the strut reduces the pressure on the lower surface of the main wing, which leads to the decrease of the lift-drag ratio.

3.2. Selection of Structural Design Parameters. For the structural design parameters of SBW, the beam model is used to model the wing, strut, and pylon. The wing, strut, and pylon are equivalent to rectangular variable section beams, and the

strength, stiffness and mass of the structure are reflected by three thickness parameters. The beam model is shown in Figure 8, and thickness parameters are shown in Table 3.

The finite element model of the structure was analyzed by changing the wingspan under the condition of 4 g upward overload. In those cases, $C_{\text{strut}} = 100 \text{ mm}$, $L_{\text{strut}} = L_{\text{wing}}/2$. t_{root} , t_{tip} , and t_{strut} are designed to satisfy the constraint of strength and stiffness. For example, the ratio of wing tip deformation to half of the wingspan is limited to 5% and the maximum stress does not exceed 400 MPa. The comparison between the SBW and the prototype in the wing mass and aerodynamic performance is shown in Table 4, using prototype's analysis results as the baseline.

It can be seen from the analysis results that the design point of $L_{\text{wing}} = 3400 \text{ mm}$ can ensure that the aerodynamic performance is better than the prototype and the mass is less than the prototype. In order to get the optimal design point, it is necessary to use a reasonable optimization method to find the optimal design point.

Taking the finite element analysis result of $L_{\text{wing}} = 4600 \text{ mm}$ as an example, the variation relationship of stress and deformation of the SBW along the span is further analyzed, as shown in Figure 9. The y -coordinate on the right is the relative deformation $\varepsilon/L_{\text{wing}}$.

The analysis results are summarized as follows:

- (1) As shown in Figure 9(a), the extreme points of stress in beam are shown in the wing root and the connection of wing and pylon. The deformation increases along the wingspan which is similar to a conventional wing. According to the distribution of stress along the wingspan, it can be seen that the reinforcement design should be carried out not only at the connection between the wing root and the fuselage but also at the wing-pylon connection
- (2) As shown in Figure 9(b), the maximum value of stress and deformation occurs near the wing-pylon connection. Similar to the wing, the strut needs to be strengthened at root strut-pylon connection to improve structural strength. In terms of deformation of the strut, the maximum deformation should be guaranteed within a reasonable range. If the distance between the strut and the wing is too close, the aerodynamic performance of the wing will be greatly disturbed and the aerodynamic efficiency of the whole UAV will be reduced

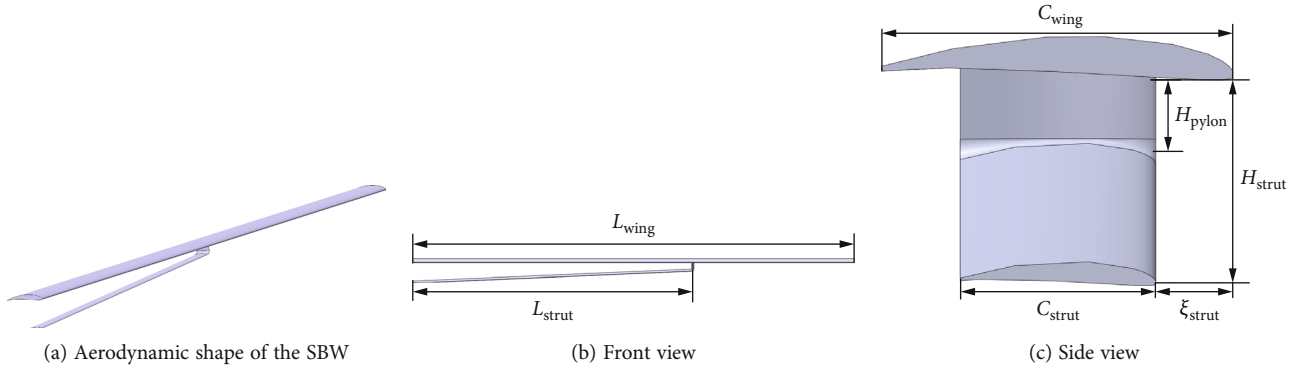


FIGURE 4: Aerodynamic design parameters.

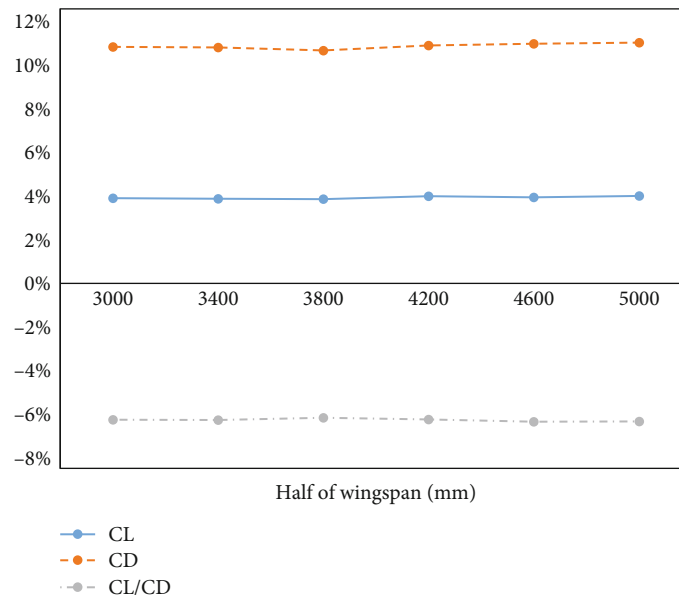


FIGURE 5: Influence of the wingspan on the lift-drag ratio.

4. MDO Model and Analysis Method

The goal of this paper is to improve the endurance of the hybrid energy UAV by using the advantages of the SBW. Because wing design directly affects many disciplines such as the aerodynamic, structure, weight, and energy, this paper adopts the MDO method to optimize the design parameters of the SBW through the tradeoffs of various disciplines to achieve the effect of improving the flight endurance.

4.1. Selection of Structural Design Parameters

4.1.1. Design Variables. The design parameters have been analyzed in Section 3, which shows that L_{wing} , L_{strut} , and C_{strut} have varying degrees of influence on aerodynamic performance; t_{root} , t_{strut} , and t_{tip} can influence the weight and structural performance. So, the 6 design parameters are chosen as the design variables of the MDO model, as shown in Table 5.

4.1.2. Objective Function. For the schematic design of the UAV proposed in this paper, the technical approaches to

improve flight endurance mainly include two aspects: (1) increasing aerodynamic performance to reduce level-flight power and (2) increasing the laying area of solar cells thus increasing the solar input power. Therefore, in this paper, from the perspective of energy consumption of the UAV in level flight, the subtraction between output power (P_{out}) and solar input power (P_{in}) in level flight is selected as the evaluation index of endurance-increasing effect and it is taken as the objective function of MDO.

The objective function is described.

$$\min (P_{out} - P_{in}) = \min f(L_{wing}, L_{strut}, C_{strut}, t_{root}, t_{strut}, t_{tip}). \quad (1)$$

According to the power balance relationship, P_{out} can be obtained.

$$T \cdot v = \eta_{prop} \cdot \eta_{motor} \cdot \eta_{esc} \cdot P_{out}. \quad (2)$$

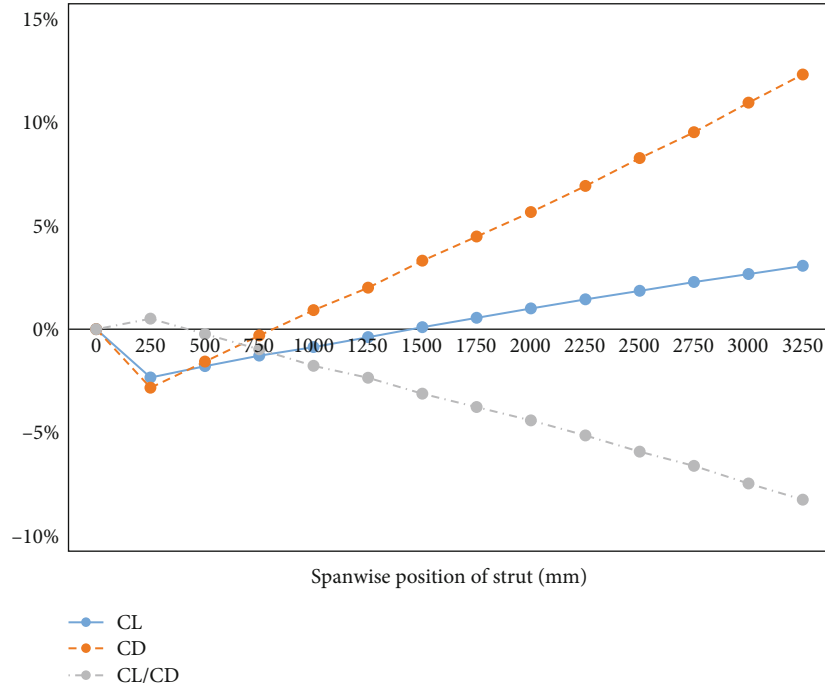


FIGURE 6: Influence of the spanwise position of the pylon on the lift-drag ratio.

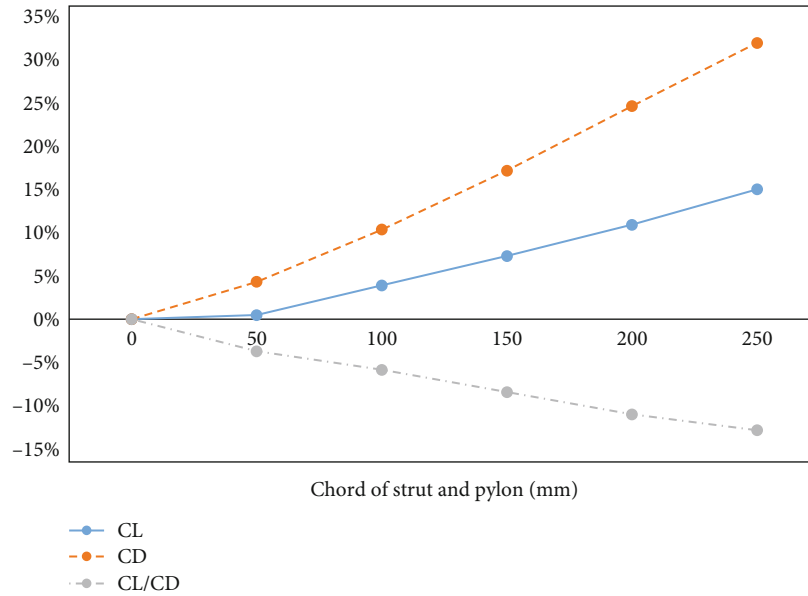


FIGURE 7: Influence of the strut chord on the lift-drag ratio.

Here, v is the level-flight velocity, T is the engine output thrust, η_{prop} , η_{motor} , and η_{esc} are the efficiency of the propeller, brushless motor, and electronic controller, respectively.

Considering the static equilibrium in level-flight,

$$\frac{C_L}{C_D} = \frac{W_{total}}{T}. \quad (3)$$

Here, C_L and C_D are the lift and drag coefficients, calculated by aerodynamic analysis. W_{total} is the takeoff weight calculated by the weight estimation module.

Combined with equations (2) and (3), the output power can be obtained as follows:

$$P_{out} = \frac{W_{total} \cdot v}{(C_L/C_D) \cdot \eta_{prop} \cdot \eta_{motor} \cdot \eta_{esc}}. \quad (4)$$

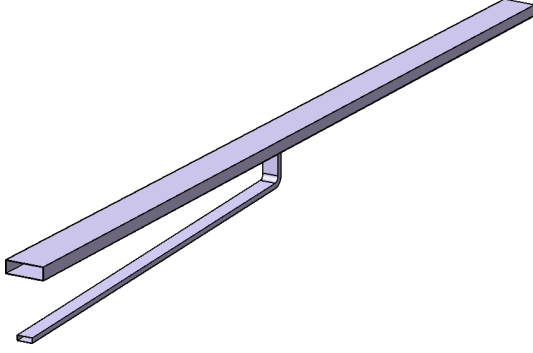


FIGURE 8: Beam model of the SBW.

TABLE 3: Design parameters of the beam model.

Number	Variable name
1	Thickness of the wing root, t_{root}
2	Thickness of the wing tip, t_{tip}
3	Thickness of the strut, t_{strut}

TABLE 4: Comparison of mass and aerodynamic performance between the SBW and the prototype.

Wingspan (mm)	Weight increment	Lift-drag ratio increment
3200	-34.0%	-0.7%
3400	-16.0%	1.0%
3800	3.6%	4.8%
4200	50.2%	8.0%
4600	105.9%	11.0%
5000	206.1%	13.6%

Rewrite the lift equation as follows:

$$v = \sqrt{\frac{2mg}{\rho S C_L}} \quad (5)$$

Combined with equations (4) and (5), the electric output power is as follows:

$$P_{out} = \frac{m^{3/2} \cdot (C_D/C_L^{3/2}) \cdot \sqrt{2g^3/\rho S}}{\eta_{prop} \cdot \eta_{motor} \cdot \eta_{esc}} \quad (6)$$

The solar input power is calculated as follows.

$$P_{in} = \eta_{angle} \eta_{MPPT} \eta_{sc} I_{sc} S_{sc} \quad (7)$$

Here, η_{angle} is the influence of the solar incidence angle and wing's curvature, η_{MPPT} is maximum power point tracking (MPPT) efficiency, η_{sc} is solar module efficiency, I_{sc} is the solar radiation on a unit (1 m^2) area, and S_{sc} is the solar module area.

4.1.3. Design Constraints. The constraint mainly considers the aerodynamics, structure, and weight disciplines. The weight discipline requires that the wing structure weight is less than or equal to the prototype. The aerodynamic performance of the SBW should be better than the prototype. Structural disciplines require the SBW structure to meet the strength and stiffness constraints. The constraints are obtained.

$$\begin{aligned} m_{total} &\leq m_{org}, \\ \frac{C_{L_{wing}}}{C_{D_{wing}}} &\geq \frac{C_{L_{org}}}{C_{D_{org}}}, \\ \sigma &\leq [\sigma]_{max}, \\ \frac{\varepsilon_{tip}}{L_{wing}} &\leq 5\%. \end{aligned} \quad (8)$$

Here, m_{total} and m_{org} are the takeoff mass of the SBW and prototype, $C_{L_{wing}}/C_{D_{wing}}$ and $C_{L_{org}}/C_{D_{org}}$ are lift-to-drag ratios of the SBW and prototype, σ is stress obtain by the structure model, $[\sigma]_{max}$ is permissible stress, and $\varepsilon_{tip}/L_{wing}$ is the ratio of wing tip deformation to the half-wingspan.

In the optimization process, in addition to the performance of aerodynamic, structural and weight constraints, the value range of each design variable needs to be considered. Therefore, geometric constraints of design variables are added to the constraints.

$$\begin{aligned} L_{wing} &\geq L_{strut}, \\ 100 \text{ mm} &\leq C_{strut} \leq 250 \text{ mm}, \\ 2 \text{ mm} &\leq t_{root}, t_{tip} \leq 20 \text{ mm}, \\ 1 \text{ mm} &\leq t_{strut} \leq 6 \text{ mm}. \end{aligned} \quad (9)$$

4.1.4. MDO Framework. According to the above analysis, the MDO model can be established.

$$\min (P_{out} - P_{in}) = \min f(L_{wing}, L_{strut}, C_{strut}, t_{root}, t_{strut}, t_{tip})$$

$$\text{s.t.} \begin{cases} m_{total} \leq m_{org}, \\ \frac{C_{L_{wing}}}{C_{D_{wing}}} \geq \frac{C_{L_{org}}}{C_{D_{org}}}, \\ \sigma \leq [\sigma]_{max}, \\ \frac{\varepsilon_{tip}}{L_{wing}} \leq 5\%, \\ L_{wing} \geq L_{strut}, \\ 100 \text{ mm} \leq C_{strut} \leq 250 \text{ mm}, \\ 2 \text{ mm} \leq t_{root}, t_{tip} \leq 20 \text{ mm}, \\ 1 \text{ mm} \leq t_{strut} \leq 6 \text{ mm}. \end{cases} \quad (10)$$

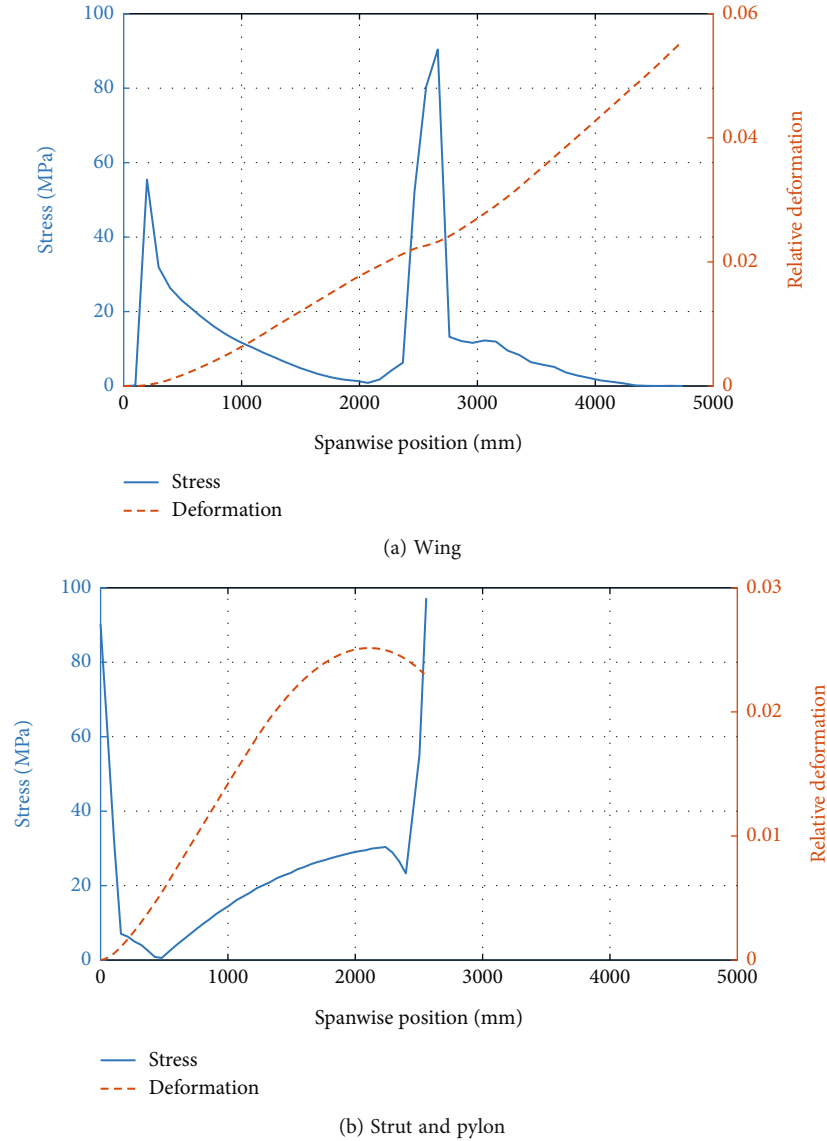


FIGURE 9: The distribution of stress and deformation along the spanwise direction.

TABLE 5: Design variables.

Disciplines	Name	Description
Aerodynamic	L_{wing}	Half of the wingspan
	L_{strut}	Spanwise position of the strut; the value is the horizontal distance between the pylon and the wing root
	C_{strut}	Strut chord length
Structure	t_{root}	Thickness of the wing root in the beam model
	t_{strut}	Thickness of the strut and pylon in the beam model
	t_{tip}	Thickness of the wing tip in the beam model

According to the MDO model and the data transfer process between disciplines, the MDO framework is shown in Figure 10.

In order to improve efficiency, the surrogate model is used to find the optimal design result, which can save calcu-

lating time and improve efficiency. The surrogate model is a simple analytical model which can mimic the input and output behavior of complex systems. In this paper, design variables are the inputs and performance of aerodynamic, structure, weight, and energy are the outputs. The surrogate

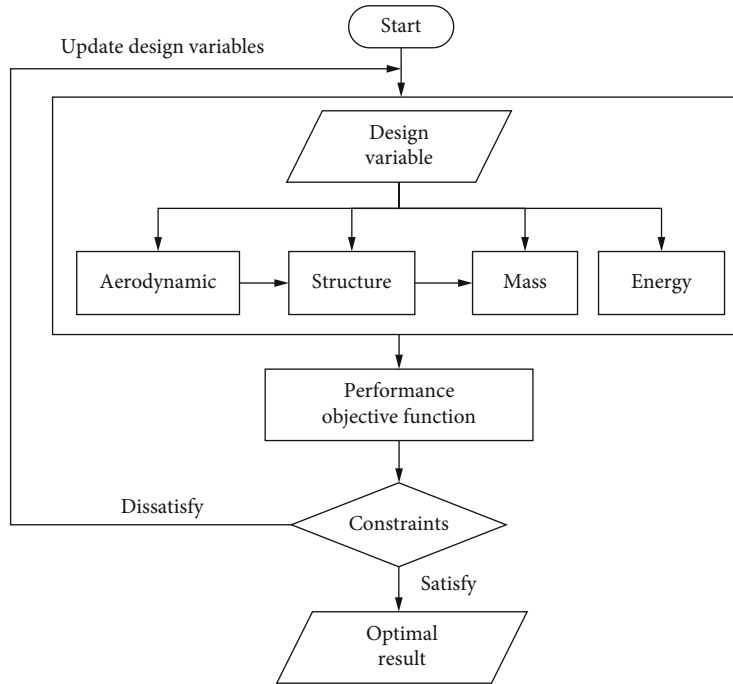


FIGURE 10: MDO framework.

model can get the approximate results of CFD and FEA without going through them. The surrogate model is implemented through the following steps:

- (1) The design points are selected according to design of the experiment (DOE)
- (2) Surrogate model technology is used to generate the surrogate model
- (3) The candidate points satisfying the minimization of objective function are optimized by the evolutionary algorithm
- (4) Verify whether the accuracy of candidate points meets the requirements. If not, add experimental design points and repeat steps (2) and (3) until the optimization results that meet the accuracy requirements are obtained

The surrogate model framework is shown in Figure 11.

4.2. Analysis Method

4.2.1. Aerodynamic Module. Aerodynamic analysis is to obtain the aerodynamic parameters of the UAV, such as lift, drag, moment, and static pressure distribution. In this paper, the CFD method based on the Navier-Stokes equation was adopted for aerodynamic analysis. Figure 12 is the CFD analysis process.

The aerodynamic analysis results need to be applied to the MDO model, so the aerodynamic analysis module needs to be parameterized. For the CFD method, the parameterization of the aerodynamic analysis module is the parameterization of the aerodynamic computing grid. The geometric

model parameterization can be used to describe the change of geometric shape and drive the change of the aerodynamic computing grid. The parameterization process of the aerodynamic analysis model is shown in Figure 13.

4.2.2. Structural Module. The engineering beam model established by the structural module reflects the strength, stiffness, and mass characteristics of the wing through the thickness of the beam. Based on the MDO model, the constraints of strength, stiffness, and weight are reflected in the structural analysis process and the analysis flow is basically the same as that of aerodynamic analysis.

The structural analysis adopts the finite element method. The structural finite element model is not only affected by the structural design variables but also affected by the aerodynamic shape design variables. Therefore, the parameterization of the structural model is jointly affected by the six design variables and the parameterization process is the same as that of the aerodynamic module.

4.2.3. Weight Estimation Module. The weight of the wing is calculated by using the rectangular variable section engineering beam, and the rest weight of the UAV is the actual weight of the prototype measured by the electronic scale.

For the hybrid energy UAV, the takeoff weight is composed of the weight of the structure (W_{struc}), energy system (W_{energy}), power system (W_{prop}), payload (W_{pld}), and others (W_{others}).

$$W_{total} = W_{struc} + W_{energy} + W_{prop} + W_{pld} + W_{others}. \quad (11)$$

The change of the wing's weight is reflected in the change of the structural weight. The constraint condition

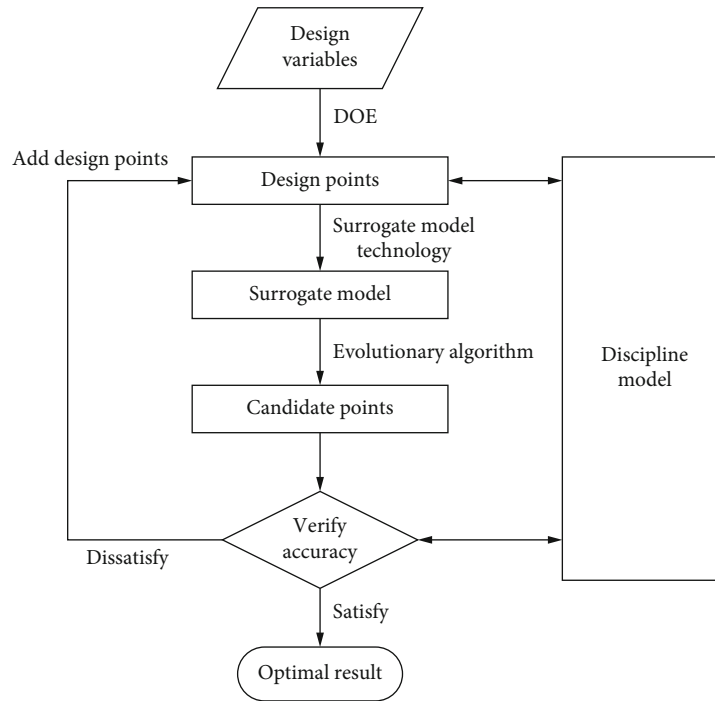


FIGURE 11: Surrogate model framework.

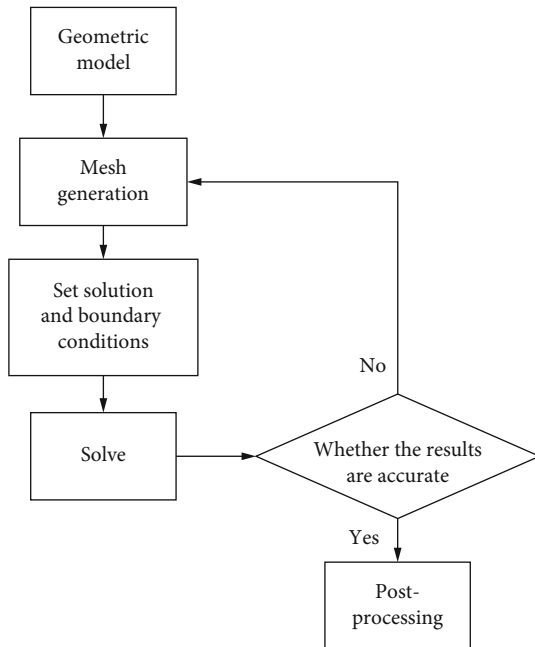


FIGURE 12: CFD flow chart.

requires that the takeoff weight is lower than that of the prototype; that means that the structural weight is lower than that of the prototype. The data of the structural weight are obtained from the geometry model.

4.2.4. *Energy Module.* The battery system provides energy for the UAV in the flight state requiring high power consumption such as the climbing stage and provides energy for the

UAV when the power generated by the solar battery system cannot maintain the level flight.

Energy consumption is reflected in the objective function of the MDO model (equation (10)). The objective function requires that the subtraction between the output power of the energy system and the power income through solar radiation in the level flight be minimized. In the level flight, the solar cell system should provide as much energy as possible to maintain the level flight, which can achieve the purpose of endurance increasing.

5. Results and Discussion

After the establishment of the MDO model and analysis methods of all disciplines, the surrogate model framework in Figure 11 is implemented in parametric geometry software, mesh generation software, and CFD software.

5.1. *Implementation of the Optimization Process.* It has been mentioned that multiple iterations will be carried out in the analysis of aerodynamic and structural modules, especially for CFD where the element size reach 2.6 million. It takes about 1 h to complete the convergence of one design point. Both the traditional gradient algorithm and the evolutionary algorithm need a lot of computing time. In order to save computing costs, the Latin hypercube sampling technique is used in DOE. Sampling and analyzing in the design space are composed of all design variables to obtain the analysis results of a set of design points. The response surface method (RSM) in the surrogate model is used to establish a second-order polynomial response surface that can reflect the relationship between design variables and objective functions.

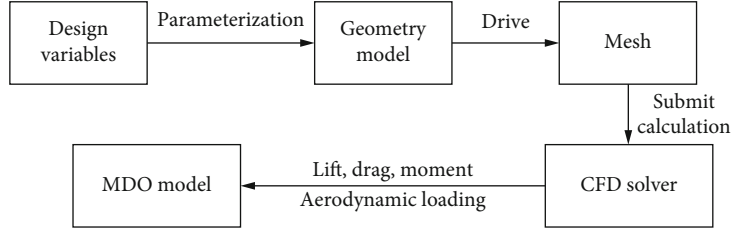


FIGURE 13: Parameterization process of the aerodynamic analysis module.

The established response surface was used for optimization, and the multiobjective genetic algorithm (MOGA) was used to obtain three candidate points, as shown in Table 6.

Both candidate points 1 and 3 can meet the constraints. Candidate point 3 has a slightly better aerodynamic performance and mass characteristics than candidate point 1, while candidate point 1 has stronger structural strength and stiffness performance and has a slightly longer wingspan than candidate point 3, which is conducive to the laying of solar cells. So, candidate point 1 is selected as the optimization result of the SBW.

5.2. *MDO Result.* The optimized result of SBW is compared with the prototype, as shown in Table 7.

From the MDO results, the following can be deduced:

- (1) The objective function of the MDO model considers the level-flight endurance-increasing effect to be optimal from the perspective of energy consumption, while the weight, structure, and aerodynamic performance are reflected in the constraints. The $P_{out} - P_{in}$ is reduced from 62.97 W to -9.67 W, which means that the UAV only needs the solar input power for maintaining level flight under this working condition. In terms of structure and weight, while the wingspan increases, the strut and pylon can enhance the strength and stiffness of the wing structure, so the weight of the wing structure is reduced. Under the balance of those two disciplines, the SBW's weight is lower than that of the prototype and can also meet the requirements of strength and stiffness constraints
- (2) Due to the existence of the strut and pylon, the SBW can increase the wingspan and aspect ratio to improve the lift coefficient of the UAV ensuring the structural and weight constraints, which also increase additional drag, so that the increment of the lift-drag ratio is not obvious
- (3) According to equation (6), it can be deduced that the output power of the energy system in level flight is proportional to m , inversely proportional to C_D/C_L , and inversely proportional to $C_L^{1/2}$. After optimization, m decreases, C_D/C_L increases, and C_D/C_L increases, which can reduce the output power. At the same time, the increment of the wingspan can also increase the income power of solar cells. Finally, the objective function value is reduced and the level-flight endurance is improved

TABLE 6: Candidate points.

Parameters	Candidate point 1	Candidate point 2	Candidate point 3
L_{wing} (m)	4.62	4.39	4.58
L_{strut} (m)	2.78	2.60	2.65
C_{strut} (m)	0.12	0.10	0.12
t_{root} (mm)	2.03	2.03	2.03
t_{tip} (mm)	1.24	1.31	1.23
t_{strut} (mm)	3.21	3.00	3.21
m_{total} (kg)	21.519	20.932	21.391
$C_{L_{wing}}/C_{D_{wing}}$	20.792	20.384	20.839
σ (MPa)	28.567	38.767	30.586
$\varepsilon_{tip}/L_{wing}$	3.44%	6.00%	3.62%
$P_{out} - P_{in}$ (W)	-9.67	5.07	-9.51

TABLE 7: The comparison between the SBW and the prototype.

Parameters	Prototype	SBW
$2L_{wing}$ (m)	6.31	9.2
C_{wing} (m)	0.423	0.423
AR	14.918	21.749
S_{wing} (m ²)	2.669	3.892
L_{strut} (m)	—	2.783
ξ_{strut} (m)	—	0.095
C_{strut} (m)	—	0.121
H_{pylon} (m)	—	0.1
H_{strut} (m)	—	0.25
m_{total} (kg)	22.396	21.519
$C_{L_{wing}}$	0.685	0.785
$C_{D_{wing}}$	0.034	0.038
$C_{L_{wing}}/C_{D_{wing}}$	20.15	20.66
σ (MPa)	35.654	28.567
$\varepsilon_{tip}/L_{wing}$	4.75%	3.44%
P_{out} (W)	358.15	337.156
P_{in} (W)	295.18	346.826
$P_{out} - P_{in}$ (W)	62.97	-9.67

6. Conclusions

This paper takes the hybrid energy UAV with the SBW as the research object, establishes the MDO model through the coupling relationship between various disciplines, and obtains the optimal design results of the hybrid energy UAV with the SBW. The main conclusions are as follows:

- (1) Applying the SBW to the new energy UAV can improve the flight endurance. The new energy UAV studied in this paper introduces the SBW configuration, rationally designs the aerodynamic shape, uses the engineering beam model to replace the complex wing structure, introduces structural strength and stiffness constraints, and obtains SBW configuration with the optimal endurance-increasing effect through the MDO. As a result of the design, compared with the conventional configuration, the output power for level flight is reduced, the income power of the solar cell system is increased, and the flight endurance is increased
- (2) The establishment process of the MDO model can provide reference for other types of new energy UAVs. In this paper, the MDO model is established through the coupling relationship between various disciplines and the relationship between the income and output power in the energy discipline is selected as the objective function, which intuitively reflects the endurance-increasing performance of the UAV
- (3) The utilization of the SBW on the basis of the conventional configuration will increase the lift and drag at the same time and will reduce the lift-to-drag ratio. Without changing the design parameters of the conventional wing, the addition of the strut and pylon will reduce the lift-to-drag ratio and adversely affect the aerodynamic performance of the wing. Therefore, the increase in the lift-to-drag ratio of the SBW obtained through the MDO is not significant

The MDO model of the new energy UAV with the SBW established in this paper and the analysis methods of various disciplines based on this model can be applied to other types of new energy UAVs. The design parameter influential analysis and MDO results can provide reference for the same type of new energy UAVs. This paper considers the coupling relationship between the aerodynamic, structure, weight, and energy but does not take into account the uncertainties in the kinematic model of level flight [21]. In future work, the authors will also consider combining the proposed MDO model with environmental disturbances and parametric uncertainties [22, 23] which will improve the robustness of UAVs.

Nomenclature

L_{wing} :	Half of wingspan
C_{wing} :	Wing chord
L_{strut} :	Spanwise position of strut

C_{strut} :	Chord of strut and pylon
ξ_{strut} :	Chordwise position of strut
H_{strut} :	Distance between wing and strut root
H_{pylon} :	Length of pylon
t_{root} :	Thickness of wing root
t_{tip} :	Thickness of wing tip
t_{strut} :	Thickness of strut
P_{out} :	Output power of energy system
P_{in} :	Solar income power
v :	Level-flight velocity
T :	Engine output thrust
η_{prop} :	Efficiency of propeller
η_{motor} :	Efficiency of brushless motor
η_{esc} :	Efficiency of electronic controller
C_L :	Lift coefficient
C_D :	Drag coefficient
W_{total} :	Takeoff weight
η_{angle} :	Influence of solar incidence angle and wing's curvature
η_{MPPT} :	Maximum power point tracking efficiency
η_{sc} :	Solar module efficiency
I_{sc} :	Solar radiation on a unit (1 m^2) area
S_{sc} :	Solar cells' area
m_{total} :	Takeoff mass of SBW
m_{org} :	Takeoff mass of prototype
σ :	Stress
$[\sigma]_{max}$:	Permissible stress
ε_{tip} :	Wing tip deformation
W_{struc} :	Structural weight
W_{energy} :	Energy system weight
W_{prop} :	Power system weight
W_{pld} :	Payload
W_{others} :	Other weight.

Data Availability

The data used to support the findings of this study are included within the supplementary information file(s). The data1.txt data which was exported from Ansys Workbench were used to support the findings of Figure 5–7. The data2.txt data which was exported from Ansys Workbench were used to support the findings of Figure 9. The data3.txt data which was exported from Ansys Workbench were used to support the findings of Tables 6 and 7.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Supplementary Materials

The supplementary material is exported from Ansys Workbench. We did not upload the source file because the data size of mesh is too large, which could not be successfully uploaded to the submission system. In date.txt, the P1, P2... are the names of the parameters. For data1.txt, P1 is half of wingspan, P2 is spanwise position of strut, P3 is

chord of strut and pylon, P4 is lift coefficient... Those parameters are defined in Ansys Workbench for CFD or FEM. The constraints and objective function are also reflected as parameters, for example, in data3.txt, P20 is the takeoff mass, P24 is the tip deformation, P38 is the lift-drag ratio, and P39 is subtraction between output power and solar input power. (*Supplementary Materials*)

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