Application of lightweight materials in structure concept design of large-scale solar energy unmanned aerial vehicle

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Abstract: Carbon fiber composites and film materials can be effectively used in light aircraft structures, especially for solar unmanned aerial vehicles. Because use of lightweight materials can reduce the weight of the aircraft, but also can effectively improve aircraft’s strength and stiffness. The large aspect ratio ratio of solar energy UAV was analyzed in detail, taking Solar-impulse solar aircraft as an example. The Solar energy UAV has a large aspect ratio greater than 20, and the detailed digital model of the wing structure including beam, ribs and skin was built, also the Finite Element Method was applied to analyze the static and dynamic performance of the structure. The upper part of the wing is covered with silicon solar cells, while the lower skin is light and transparent film. The single beam truss form of carbon fiber lightweight material is used in the wing structure. The wing beam is a box beam with rectangular cross sections. The fuselage of the aircraft was built by space truss structure. According to the static and dynamic analysis with Finite Element method, it was found that the aircraft has a small wingtip deflection relative to the wingspan in the level flight state. The first natural frequency of the wing structure is pretty low, which is closed to the gust load.

1. Introduction

Setting solar cells on the aircraft and manufacturing solar powered aircraft is the most creative application of solar cells. Transferring solar radiation energy into electric energy to drive the electric propeller for the solar powered aircraft can stay at an altitude of 10-30 km for several months every year, contributing itself a bright prospect on environmental monitoring, border patrol, data link relay, etc[1,2]. Apart from related conception research, many researchers have completed the engineering validation study of High-altitude Long-endurance Unmanned Aerial Vehicle. As one of the famous solar powered drone, American “Helios” [3] lasted for 4 hours at an altitude of 29,531 m in region which is 18 degrees north latitude of Hawaii on August 13, 2001, breaking the record of maximum ceiling of propeller powered fixed-wing aircraft. As for the most well-known solar powered aircraft, “Solar-impulse” adopts conventional wing layout with a span (63m) approximately equal to A380 of AIRBUS, but surprisingly, it merely weighs like a family car. What’s more, there are totally 11.628 thousand solar cells covering an area of 200 m² on its straight wing and horizontal tail. Currently “Solar-impulse” can’t fly at night and above 10 thousand meters. In Feb, 2014, the advanced “Solar-impulse II” finished its first flight. Compared with the former, its weight of structure has increased from 1600kg to 2300kg, its span from 63m to 72m. The aircraft carried out a global flight in 2015 and passed through China. In this study, the application of lightweight materials in the
conceptual design of solar energy unmanned aerial vehicles was carried out including the static analysis and modal analysis of the wing structure.

2. Structure layout

The structure of the wing has a large surface ratio, large aspect ratio and large span characteristics. The main materials of wing are carbon fiber honeycomb composites, and the upper skin is covered with a layer of solar cells, while the lower skin is covered with a layer of lightweight transparent film. Wing ribs are installed between the two layers to support an form the aerodynamic shape. Like "Solar impulse", low speed thick airfoil with large chord length was used in wing design, and also with slender wing trailing edge to expand the wing area for more solar cells. The performance of the "Solar-impulse" aircraft as a reference [4], the overall size parameters are as follows.

Table 1. Summary of Solar Impulse HB-SIA features [4]

| Parameter         | Value       |
|-------------------|-------------|
| Wing span         | 63.4m       |
| Cruising speed    | 70km/h      |
| Fuselage length   | 21.85m      |
| Max. Altitude     | 8500m       |
| Fuselage height   | 6.4m        |
| Empty weight      | 1600kg      |
| Takeoff speed     | 35km/h      |

According to reference [4,5], the detailed measurements of wing structure were designed. The partial measurements of the wing and some parts are as follows: The wing is divided into inner and outer segments. The unilateral inner wing measures about 20.25m long, outer segment about 11.45m long including winglet. The chord length of inner wing is approximately 1.5 times, and the dihedral of the outer segment is about 8 degrees. The whole wing has 120 wing ribs when 80 wing ribs are in inner wing and the other are in both left and right outer wings. The measurements of wing ribs of outer wing segment decrease linearly. And in the inner segment the largest wing rib is 1.5 times bigger than the smallest one.

The wing rib is composite structure, the front and rear portions of it are joined together by a rectangular beam. The ribs can bear the local aerodynamic force transferred from the skin to rectangular beam then, which will produce bending moment on wing ribs, so it’s effective for bearing the unexpected bending moments and add some support structure in wing ribs. The bending moment at wing root becomes incredibly large with the wing span extending, hence, it’s important to decrease the weight of wing structure. New materials with high specific stiffness and lightening hole are efficiently designed for decreasing weight.

The wing beam is rectangular in shape and composed of closed box sections when the rectangular beam support all the structure, which solves the problem about the large bending moment at wing root for aircraft with large aspect ratio. The 7th wing rib from the plane of wing symmetry is installed with a propeller, and it only contributes a little of moment on account of the short distance away from wing root, its impact on the wing is not pivotal. Moreover, there is also an electric propeller where the inner and outer wing segments joint and it can balance wing lift when the aircraft flies. The biggest rib is a truss structure with height of 0.42m, and it is divided into 6 sections. The length of each section is 0.8m, 0.7m, 0.6m, 0.3m, 0.3m and 0.45m from the back of the ribs (Figure 1).

![Figure 1. The wing and ribs layout.](image-url)
The fuselage length is 21m, accounting for 1/3 of wing length, and the fuselage width is 0.4m (Figure 2). The nose which is truss structure which is located below the plane of wing symmetry, and there is a equipment compartment in the head, which can accommodate other equipment such as satellite antenna. The space truss structure is the main form of the aircraft fuselage, and 4 longitudinal flanges make up the main structure of the aircraft fuselage when vertical and oblique carbon fiber brackets support the adjacent flanges.

The horizontal tail is connected with fuselage likes upper wing layout, and horizontal stabilizer and elevator constitute the horizontal tail which has 24 ribs. The horizontal tail consists of horizontal stabilizer and a rudder, containing 24 ribs, and uses approximately symmetrical airfoil with lightening hole on each rib which joints together with a rectangular beam. The horizontal tail measures 9.12m long and 0.33m wide, while the vertical tail is vertically embedded in the fuselage tail. Similarly the vertical tail uses symmetrical airfoil whose chord length is 1.65m, maximum thickness 0.33m, span 6.4m, and it has 13 ribs (Figure 2).

**Figure 2.** Fuselage detailed structures, horizontal and vertical tail detailed structures [5].

### 3. Static analysis of wing structure

The main material of the wing beam is carbon fiber which is quite suitable for aircraft with large aspect ratio because of its small density, large stiffness and large elastic modulus. However, decreasing the weight of wing ribs matters in contrast to the requirements of stiffness, and it means that carbon fiber honeycomb sandwich can be used. The skin is the primary part to support the aerodynamic force, so the small density polyester film which doesn’t damage easily when suffering huge deformation is suitable. Material properties are shown in the following table.

| Material            | Density (kg/m³) | Elastic Modulus (GPa) | Poisson Ratio |
|---------------------|------------------|------------------------|--------------|
| Carbon-Fiber        | 1400             | 200                    | 0.3          |
| Carbon Fiber Honeycomb Sandwich | 350             | 100                    | 0.3          |
| PET Film            | 1450             | 3.495                  | 0.3          |

The measurements of the hollow rectangular beam are as follows: width (0.5~0.6m), height (0.2~0.3m), wall thickness 1~2cm. The weight (400N) of motor and corresponding propulsion device are respectively imposed on the 7th wing rib and the 40th rib from the fuselage in the form of concentrated force [5]. What’s more, the weight of solar batteries and structure are imposed on the wing beam in the form of approximative distributed force. The structural finite element calculations were performed with the MSC. Patran/Nastran software under the action of gravity. After calculating and analyzing, the maximum displacement of wing is -0.808m showing at the wing tip, and at the wing root comes the maximum stress shown as 2.64MPa. In level flight state where the wing lift equals the aircraft weight. It is assumed that the whole lift is generated by the wing, and the lift on the wing is distributed according to the ellipse. The maximum displacement of the wing is 0.371m at wing tip, the maximum stress is 1.54MPa far below the ultimate strength at the wing root (Figure 3).
Figure 3. Displacement and stress distribution in level flight state.

4. **Natural modal analysis of the wing structure**

The modal frequency of wing is found low through modal analysis, and its main modal frequency is in the range of 0-20Hz, basically consistent with the conclusion of reference [5]. The low order mode of wing is close to the frequency of gust load. The first order modal frequency is about 0.6Hz and the vibration mode is a bending mode on the vertical direction.

| Modal   | Frequency | Modal   | Frequency |
|---------|-----------|---------|-----------|
| First   | 0.64      | Third   | 3.98      |
| Second  | 1.22      | Fourth  | 7.11      |
Freq.=0.64186

Freq.=1.2208

Freq.=3.9808

retracted
5. Conclusion

Lightweight materials were used in the Solar UAV structure design which took the "Solar-impulse" aircraft as a reference. The aspect ratio of the wing is more than 20, resulting in low wing structure stiffness. If encountering gale and gust load, the wing structure will resonate with a huge bending deflection appearing, that may result in structural damage of solar batteries. The fragile mechanical properties of solar silicon cells taken into consideration, in order to achieve practical purposes, double fuselage structure layout will effectively increase the structural stiffness of such aircraft in future.

References
[1] Yan Yan-fa. Status and Challenges of Thin-film Solar Cells. Optics & Optoelectronic Technology. 2015.13(6):1-4.
[2] Chang min, Zhou Zhou, Wang Rui. Primary Parameters Determination for Year-round Solar-powered Aircraft of Wing Fold Type at Higher Latitudes. Acta Aeronautica et Astronautica Sinica. 2013.34(1):1-11.
[3] Stanley R. Herwitz. Orchestrating A near-real-time imaging mission in national airspace using a Solar-Powered UAV. AIAA.2003-6617:1-10.
[4] Marc Boeswald, Arne Vollan, Yves Govers, Peter Frei. Solar Impulse-Ground Vibration testing And Finite element Model Validation Of LightWeight Aircraft . IFASD-2011-132.
[5] Around the world in a solar airplane. [EB/OL]. [2015-03-24]. http://www.solar-impulse.com.
[6] Yin ChengYue, Gao PuYun, Guo jian, et.al. Mechanical performance analysis on wing’s of Zephyr7 UAV. Structure & Environment Engineering. 2009.39(3):19-25.