Design and experimental structural analysis of a solar powered aircraft wing structure

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Abstract. Structural architecture plays a vital role in the design of solar powered aircraft. Wing analysis is critical as wings experience different loads and stresses. The objective of this work is to explore the use of renewable energy sources in aircraft technology in the form of solar-powered aircraft. The number of solar panels needed for a manned aircraft is determined based on the several solar factors. Thus this paper initially deals with the design of the wing structure for a solar powered two-seater aircraft. Also, the present work experimentally analyses the structural responses of a composite wing panel with and without the solar panel which makes this study significant.

1. Introduction

Natural resources like fossil fuels are causing tremendous harm to environment. So, human started attempts to harness the renewable energy such as solar, wind, geothermal and hydroelectric resources. Even though solar energy is used as a source of electricity, there is huge portion remain unutilized [1]. In 2002, it was estimated that energy used by the world for the complete year is lesser than energy obtained from the sun in one hour. Flying without the usage of conventional fossil fuels is an area of importance because of the alarms on rise in global warming and a declination in natural resources. Solar aircraft is one of the best ways to make use of solar energy [2]. In advancement series of solar and electrochemical cells, studies started scrutinizing high altitude solar powered unmanned aerial vehicles. Initially it flew with radio controllers and battery power as it was not Equationuipped with the solar cells. Even after having legalized aerodynamics it was kept aside for ten years because of its impulsive solar cells and energy storage technology. In 1993, it was fitted with solar cells by ballistic missile defence organization and five low altitude flights were flown successively. Hy-Bird project [3] was powered completely by renewable solar energy and hydrogen, without effusion of greenhouse gases and noise pollution. The solar cells append on the wing and tail and produce power for an electric engine to take-off and cruise. Solar Powered Aircrafts (SPA) can be employed for several purposes like aerial monitoring. Solar cells can be connected to an electronic circuit which can deliver sufficient power for the motor and other avionics and excess energy can be stored in the battery which will also serve while flying in dark or beneath clouds. The problems of the SPA include geographical area of operation, energy collection and storage, payload and design parameters. The key concept is to make use of the renewable solar energy by turning it into electricity by means of solar cells installed on the structure. Structural architecture and analysis possess a significant role in any aircraft design.
The structural strength is obtained based on the load factor that the aircraft can endure at a specific speed [4]. Numerous papers are available to analyse the behaviour of aircraft wings. However, very little literature on green aviation is available. The SPA is a research area in progress. Important works related to the present study are cited in this section.

The solar aircraft may be of conventional design with respect to the basic components of the aircraft. The characteristics of solar cells and practical aspects of design were scrutinized from the previous research papers. The necessary solar energy availability is between 6 am to 6 pm. Since solar energy is not obtainable during night, energy should be secured for aircraft to aloft overnight [5-6]. Energy can be stocked by storing in the batteries. William et al [7] provided some analytical advances that could be helpful in the estimation of the performance features of SPA. Projected developments of fuel-cell energy storage systems appear to make the SPA feasible. As the currently available rechargeable batteries are too heavy, it is not viable to operate SPA [6-8]. Wing loading is the main design parameter [9] to be considered as the power necessary for flying depends on it rather than the component characteristics.

As noted above, several previous wing designs and research didn’t acknowledge the inclusion of solar cells. However several recent studies have mentioned the impact of solar energy on unmanned micro air vehicles. The purpose of this work is therefore to discuss the concept of a SPA wing, for a manned 2-seater SPA. Present investigation explores on resizing a traditional wing, so that the solar panels can be integrated into wing in compliance with the power requirements. It also addresses the experimental study of solar panels in certain aircraft wing construction.

2. Numerical modelling

For a steady level flight, the aerodynamic lift should be equal to the overall weight of an aircraft and the obtainable energy during a day from the solar panel should be greater than or equal to the required power of an aircraft. The airfoil chosen is NACA 23018. As the performance of the C-60 photovoltaic cells was 22% and the standard silicon solar cells were just 15%, the C-60 cells were designed to have a stable voltage. At steady-level flight, the lifting force produced by the wing precisely compensates for the weight and the thrust of the propeller for the drag force. The weight of the steady-level aircraft shall be determined by:

\[ W = L = \frac{\rho V^2 S C_L}{2} \]

where \( L \) represents the lift; \( \rho \) denotes the density of air (kg/m\(^3\)); \( S \) is the planform area of wing (m\(^2\)); \( V \) is the aircraft’s cruise velocity (m/s). Power required for level flight is got using:

\[ P_{req} = T \times V. \]

Estimation of power available from solar energy is discussed below. Initially, the location where the airplane is going to fly is to be specified. It is important to calculate the solar energy available at that specific spot. Thanjavur, India is taken as the location and the latitude (\( \psi \)) is 10.72°. The power available is assessed based on the solar energy obtained as of April 1, 2018. For April, the \( n \) value is 92, as the sequence of the numbers begins on 1 January. From this the angle of declination (\( \lambda \)) can be determined by Equation (1).

\[ \lambda = 23.45 \sin \left( \frac{360 \times \frac{248 + x}{365}}{365} \right) \]

The hour angle can be determined using the latitude and the angle of declination as in Equation (2).

\[ A = \cos^{-1} (\tan \psi \times \tan \lambda) \]

Using the Equation (3), the daily average irradiance can be found.
\[ F_0 = \frac{24}{\pi} (I + 3600(1 + 0.033(\cos \frac{360x}{365}))(\lambda \sin \psi \sin \lambda + \cos \psi \cos \lambda \sin \lambda)) \text{KJ/m}^2\text{day} \]  \hspace{1cm} (3)

where \( I \) denotes the extra-terrestrial irradiance. The Equation (4) determines the day length

\[ k = \frac{2}{15} \cos^{-1}(-\tan \psi \tan \lambda) \]  \hspace{1cm} (4)

By using Equation (5), the monthly average daily global radiation (\( F \)) can be calculated.

\[ \frac{F}{F_0} = p + q \left(\frac{k'}{k}\right) \]  \hspace{1cm} (5)

where

\[ p = -0.309 + 0.539 \cos \psi - 0.0693D + 0.29 \left(\frac{k'}{k}\right) \]

\[ q = 1.527 - 1.027 \cos \phi + 0.0926D - 0.359 \left(\frac{k'}{k}\right) \]

where \( k' \) is the average sunshine hour per day and \( D \) is the altitude of the place above the mean sea level (88 m for Thanjavur). The instantaneous hour angle for a specific hour \( t \) can be derived using Equation (6).

\[ \sigma = (15t - 180) \]  \hspace{1cm} (6)

Hourly global solar irradiance is presented in Equation (7).

\[ I_g = \left[ \frac{\pi}{24} \left( u + v \cos \sigma \right) \left( \frac{\cos \sigma - \cos \sigma_k}{\sin \sigma_k - \frac{\pi \sigma_k}{180} \cos \sigma_k} \right) \right] * F; \]

\[ u = 0.409 + 0.516 * \sin(\sigma_k - 60), v = 0.6609 - 0.4767 * \sin(\sigma_k - 60) \]  \hspace{1cm} (7)

3. Results

The SPA wing design details and the results of performing the structural analysis of composite wing panels incorporated with solar cell is presented in this section.

3.1 SPA wing design

Mission requirements considered are: Payload = 150 kg, total weight = 30,000 N, and altitude = 8500 m. Also the average air density = 0.5252 kg/m^3 and clearance factor = 0.7 is considered. The solar cell length and width is 0.125m, solar cell efficiency is 22 percent, solar panel area is 0.0150 m^2, rated current is 5.37 A and rated voltage is 0.57 V. The airfoil lift coefficient is 0.91. The overall drag is obtained from the drags produced by the wing \( C_d \) (which is 0.00874 N), the induced drag (which is 0.7855 N), and due to the body, (which is 1.7 times by the airfoil drag). Thus the gross drag on the whole airplane is 77.11 N. Since we have the gross drag force and the flight velocity values, the power needed can be found: \( P_{\text{Equation}} = T \times V = 3085 \text{ W} \). For obtaining this much power, extra power has to be taken from the battery and to consider the losses in electronic circuits. Therefore, 127823.54 W m^-2 of solar irradiance is needed in order to provide a level flight. Now, calculations are to be done to know whether this much solar irradiance is available from the sun.
Solar parametric values are calculated for the place (Thanjavur) at a latitude (\(\phi\)) of 10.72°. Using the equations discussed in section 2, the angle of declination is 4.809° and the hour angle at this place is 89.08°. The average length of the day is estimated as 12.12 hours. The global solar irradiance can be now estimated for each solar hour by considering the clear sky factor as 0.7. The wing planform area of the SPA shall be calculated on the basis of the power needed for the level flight, obtained as 127823.54 W/m². Area of the solar panel incorporated is 0.0150 m² and a single panel possessing an efficiency of 22% will generate 3.06 W/m² power. The number of cells required is estimated to find the area of wing planform. Since the number of cells is set the minimum wing area is calculated. The corresponding area is measured to be 132 m². This field requirement is accomplished by taking the chord of 2 m as well as the wing span of 66 m. Thus the wing span is estimated to be 66m for the present SPA (as the chord kept equal to 2 m, as similar to conventional wing case). Thus, the revised wing configuration suited to the facets of solar power is obtained and presented in ‘figure 1’.

![Figure 1](image1.jpg)

**Figure 1.** Comparing the conventional wing structure with the modified wing structure for SPA

### 3.2 Experimental analysis of composite wing with and without solar panel

Finally, a small scale solar powered composite wing was manufactured (‘Figure 2’) and structural analysis has been performed. Glass-epoxy composite was manufactured initially and taken as the base structure and the solar panel was attached over it. Composites are highly significant in aerospace applications because of its specific strength and other advantages.

![Figure 2a and 2b](image2.jpg)

**Figure 2a.** Composite without solar panel  **Figure 2b.** Composite with solar panel

Structural analysis was carried out experimentally for the composite wing with solar panel and without solar panel. Bending analysis results for the composite wing panels shown in ‘figure 2’ are discussed.
in this section. Plots were made between load and deflection for composite plate structure with solar panel (on the top) and without solar panel. Experimental set up used is given in ‘figure 3’. Four dial gauges, two supports, two hooks, weights of 200 g each (maximum 10), nuts and bolts, composite wing with solar panel, composite wing without solar panel were used for experimental analyses. Dial gauges were used to measure deflection. The length, breadth and thickness of both the composite wing panels considered are 278 mm × 120 mm × 4 mm. Holes of diameter 5 mm are made at the free end of composite panel to hang the weights using the hooks. Two supports are used to fix the composite wing panel with nuts and bolts at the other end. Initially, only one hook is placed at the centre hole and weights are added in the increments of 200 gm till 2 kg. The deflection values from the dial gauge are noted for each increment in load. Thus the bending values are calculated at different points. Thus bending analysis is carried out. The graph is plotted between load and deflection for the tabulated values as in ‘figure 4’. Also, tension tests were conducted (test method: ASTM A638) for composite panel with and without solar panel and the results obtained are presented in ‘figures. 5-6’. It was noted from the experiment that \( F_{\text{max}} \) was 3.88 kN and 3.89 kN for the present composite panel with and without solar panel. Also the maximum stress was observed as 64.12 MPa and 64.31 MPa for the present composite panel with and without solar panel respectively. There is no much variation in the results obtained for the bending analysis of composite wing with solar panel and without the solar panel. Thus it is noted that placing a solar panel on the top of the composite base is not affecting the structure much.

Figure 3. Experimental set up
Figure 4. Bending analysis of composite panel with and without solar panel

Figure 5. Tension test for composite panel without solar panel
4. Conclusion
The present investigation deals with the structural design and experimental structural analysis of wing panels for SPA. A conventional wing was re-sized for same loading to combine solar power features. Calculations were presented to estimate the number of solar cells necessary for producing lift of an aircraft and then the wing is designed as per the number of solar cells necessary. This gives a basic idea to design a manned (two seater) solar powered aircraft. By taking a chord of 2 m and wing span of 66 m, the solar powered aircraft criterion is achieved in present analysis. Later, a composite wing panel with and without solar panels were considered and experimentally studied the bending response. It has been noted that placing a solar panel on the top of the composite wing will not affect the structure, but it will provide the greater significance, as it utilizes renewable energy.

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