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Solar array layout optimization for stratospheric airships using numerical method

Mingyun Lv, Jun Li *, Huafei Du, Weiyu Zhu, Junhui Meng

School of Aeronautic Science and Engineering, Beihang University, 37 Xueyuan Road, Beijing 100191, PR China

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ABSTRACT

The solar array layout is one of the critical factors affecting the output performance of a solar array on a stratospheric airship. Optimizing the layout to improve output energy per day is very important for a long endurance vehicle, but the research about this subject is rare. This paper outlines a numerical method based on a rotating model of a stratospheric airship to optimize the solar array layout. Combined with the solar radiation model, the solar array layout optimization model applying genetic algorithm is developed using a MATLAB computer program in this paper. Compared with the design parameters of three stratospheric solar-powered airships, the theoretical model is proved to be feasible. In the course of the study, the effects of the starting point and the central angle of solar array are discussed in detail. In addition, the optimal results of the solar array layout for four common situations are investigated using the method. The results indicate that this method is helpful in the preparation stage for installing large area flexible solar arrays.

1. Introduction

With potential for scientific exploration as well as for observation and surveillance, there is growing interest in studying stratospheric airship as a long endurance vehicle in recent years [1].

For geostationary stratospheric airships, solar energy is one of the most ideal of renewable energy to achieve the ability to fly for an extended duration of time at high altitudes [2]. Therefore, many studies have been carried out previously to survey the feasibility of stratospheric solar-powered airships. For any type of long endurance vehicle, Colozza [3,4] expatiated that technologies such as thin film solar arrays, fuel cells, electrolyzers and power management were the key elements in the feasibility of achieving long duration high altitude flight. A number of factors such as the operational environment and efficiencies of the power system components which can influence the energy balance of a stratospheric solar-powered airship were listed by Colozza. Eguchi and Yokomaku [5] researched the feasibility of stratospheric platform airship during 18 months from Spring 1998 and found that the stratospheric airship system might be realized with advanced component technologies. The key technologies of feasibility study program included design and manufacturing of a huge lightweight envelope, a clean solar power generation system with photovoltaics and fuel cells and so on.

As mentioned in the foregoing description, it can be seen that the stratospheric solar-powered airships with ability of station-keeping at high altitude is feasible. Based on the result, many investigations on solar array of stratospheric airship have been published. Wang [6] partitioned the flexible solar cells of a curved surface on the back of the airship into n (along with heading) × m (along with circumference) grids, and each grid can be seen as a tilted plane. In addition, the authors developed their computation method to study the effect of the high-altitude airship's attitude on the performance of its energy system when the airship is flying in 40° north latitude region in winter and summer solstice. Su Song [7] developed a higher precision model that was used for investigating the output performance of the curved surface solar cell. The stratospheric airship was simplified as the cylindrical vehicle to analyze the power characteristic of the solar array and the effects of operation time, latitude, attitude, installation geometry of the array of the airship on the power [8]. An approach is proposed to calculate the incident solar energy on complex airship hull profiles and a method was suggested to study the solar energy required. Furthermore, the authors estimate the needed areas of the solar array [9].

Based on previous research results, it can be seen that the output performance of solar array is sensitive to a number of factors, such as flight location, date of task, and solar array layout [6,9].

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* Corresponding author.
E-mail address: geniuslee215@buaa.edu.cn (J. Li).

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Nomenclature

A	the calibration factors at low altitudeand high altitude
c_{high}	the calibration factor at high altitude
c_{low}	the calibration factor at low altitude
D	the maximum diameter of airhsip, m
e_e	orbital eccentricity
$\vec{n}$	normal vector of tilted grid
I_0	solar constant, $I_0 = 1367\ \mathrm{W/m^2}$
I_h	the direct solar irradiance, $\mathrm{W/m^2}$
I_s	scattered radiation, $\mathrm{W/m^2}$
I_R	the reflected radiation, $\mathrm{W/m^2}$
l_{SA}	the length of the solar array, m
L	total length of the airship, m
$\vec{n}_s$	unit vector of solar direct radiation
$\vec{n}_{ij}$	the normal vector of grid *ij*
n_{ijI}	the expression of the normal vector of tilted grid *ij* in the inertial frame of reference
p_h, p_0	the atmospheric pressure at the altitude h and the sea level, reflectivity
q	radiation on the tilted grid, W
Q	total radiation on solar array, W
r	the equivalent rotary radius of airship, m
R	the transformation matrix from the body coordinate system to the inertial frame of reference
r_e	the radius of earth, m
r_{sky}	the reflectivity of sky
x	chordwise coordinate
x_{ij}, z_{ij}	the x and z coordinates of the central point of tilted grid *ij*
y	chordwise coordinate
z	vertical coordinate
y_1	the y coordinate of leading edge of solar array
y_2	the y coordinate of trailing edge of solar array
α_e	absorptivity of solar array to direct incident
α_i	included angle between the plane normal and the gravity direction
α_R	absorptivity of solar array to reflected radiation
θ	central angles of solar array, degrees
θ_{ele}	solar elevation angle, degrees
θ_{ami}	solar azimuth angle, degrees
θ_{DIP}	the angle of view at the altitude h, degrees
ψ	yaw angle, degrees
φ	pitch angle, degrees
ϕ	roll angle, degrees
λ_{am}	air mass ratio, degrees
λ_e	the true anomaly
δ_{array}	the transmissivity of external encapsulation layer of solar array
τ_h	the transmissivity of a solar beam thru the atmosphere
ω	the weighting coefficients that can characterize the influence of different wavelengths of light on solar cells
ω_{sign1}	projection coefficient of solar direct radiation on the tilted grid

Subscripts

SA	solar array
dij	direct solar radiation on tilted grid *ij*
sij	scattered radiation on tilted grid *ij*
Rij	reflected radiation on tilted grid *ij*
h	the altitude *h*
ij	tilted grid *ij*

Sun et al. [10] developed a mathematical model to investigate the solar radiation and output power characteristics of the thin film solar array and research the influences of flight time, flight location, flight status and other factors on the output power of the solar cell arrays. Zhang et al. [11] developed a simplified analytical model to research the effects of airship's latitudes, pitch angles, four yaw angles and the solar array layout on the output power of solar array. It can be found that the effects of solar array layouts are different when the latitude and date are different. According to these results, the solar array layout needs to be adjusted with the change of flight area and date. However, the detailed studies of the layout effect have rarely been done in their works.

For a large area flexible solar array, the application of modularized design makes it easy to change the solar array layout before the airships launch [12]. Solar cells at different positions of the curved envelope output inequable power during the daytime. Then it is very necessary that every piece of solar cell is placed in the most suitable position. So solar array layout optimization is very important for long endurance airships. But the related research is rarely worked.

The purpose of the present study was to present a numerical method for reducing the area and weight of the solar array by using a kind of suitable optimization algorithm. Over the last few decades, to solve the similar problems, the scholars from countries all over the world have proposed various optimization algorithms, namely, swarm optimization algorithm [13] and evolutionary algorithm [14,15], especially genetic algorithm [16]. Genetic algorithm which is classified as one of the evolutionary algorithms [17], is chosen in this work due to its capability of determining global optimum solutions over a series of iterations (generations) throughout the search space.

In this paper, a numerical model is developed for investigating the effects of solar array layouts on the output power. In addition, solar array layouts are optimized for four common airship operating conditions by using genetic algorithm. The results are helpful in guiding to install suitable solar array for long endurance airships.

2. Theory

To optimize the solar array layout on a stratospheric airship, the stratospheric airship subjected to a payload is idealized to be a streamlined rotating airship [18] as shown in Fig. 1. y_1 is the y coordinate of leading edge of solar array. y_2 is the y coordinate of trailing edge of solar array. θ is the central angle of solar array, and $\theta \in (-\pi, \pi)$. l_{SA} is the length of the solar array. y_2 and l_{SA} are the functions of y_1 and θ when the area of solar array is constant. In addition, several fundamental parameters of this stratospheric airship are listed in this paper as follows:

1. the total length of the airship, L, is 220 m,
2. the maximum diameter is, D, 54 m,
3. the ceiling altitude of the stratospheric airship is about 20 km,
4. the efficiency of the solar cell is assumed 12% in this paper [6].