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Optimization of solar-powered hybrid airship conceptual design

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A R T I C L E I N F O

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This paper aims to develop a high-altitude solar-powered hybrid airship, which combines aerodynamic lift and buoyancy with buoyancy force and cruises continuously. A multi-lobed configuration is employed and the solar irradiance and photovoltaic array model are proposed. After introducing all the parts mass of the hybrid airship and design procedure, an optimal problem with the constraint of energy and the equilibrium between buoyancy and weight are proposed. Through a hybrid optimization search method, the solution is obtained and the sensitivities of geographical location and seasons are discussed. The results show a comprehensive influence of the constraint both in latitude and wind field environment.

1. Introduction

Development of hybrid airships has been an important stream in both the military and civil aviation industries for decades and will continue to draw great attention in the future. The novel projects develop rapidly in decades such as Lockheed Martin Sky-Tug, Hybrid Air Vehicles Airlander 50 [1] which can carry dozens of tons cargo for remote transportation. In addition, hybrid airship as a high altitude platform can cruise and loiter in the stratosphere for remote reconnaissance and ground surveillance mission [2,3].

Generally, the hybrid airship is a new configuration combining static buoyancy with aerodynamic lift produced by lifting body and vector thrust. One of the important differences from conventional airship is an improved aerodynamic configuration which generates a considerable amount of lift such as delta lifting body, winged and multi-lobed shapes [4–9]. With a multi-lift source and high lift–drag ratio, hybrid airship has an adjustable buoyancy ratio (BR) which plays an important role distinct from the conventional one. Based on an great improvement on changeable lift, hybrid airship can adjust the altitude flexibly to overcome different weather, wind field and mission requirement. And the performance is also distinctly different among various configurations such as winged and multi-lobed ones.

In addition, as a result of the development of regenerative power lately, clean energies are gradually applied as more durable and stable power for high altitude hybrid airship such as solar energy which seems to be inexhaustible [10,11]. Regardless of aircraft types, HAA [12] and HALE [13,14] can both achieve several days flight using photovoltaic array panels for propulsion power. However, the efficiency of the flexible solar cell is only 8% [15], though the rigid one has a nearly 30% efficiency [16]. And the energy supply during the night is also a tough challenge for storage [17]. It is noteworthy that the fuel cells have more than 1000 w h/kg [18] specific energy density than lithium battery with a 200∼300 w h/kg, which will be a great potential application and weight reduction in energy storage system during night [17]. With an aerodynamic advantage and potential energy system, high altitude hybrid airship design and manufacture are undergoing rapid development accordingly.

A methodology for sizing of high altitude unconventional airship was proposed by Ceruti [19], the methodology presented a parametric approach considering the evolution in materials and technology, new configurations, and modern power and demonstrated a graphical and straightforward mathematical operations to obtain the solutions. A Multi Disciplinary Optimization (MDO) [20] was also presented with heuristic algorithms to optimize the aerodynamic shape. A comparison among these algorithms has indicated that the genetic algorithm (GA) and Particle Swarm Optimization(PSO) had better results than Simulated Annealing (SA) and Monte-Carlo method. Song et al. [2] demonstrated a high altitude winged airship with solar array atop the body and wing. A Non-dominated Sorted Genetic Algorithm optimization has been carried out to determine the configuration parameters with different cruise modes for day and night. Jenkins et al. [21] proposed an optimization design method using a genetic algorithm (GA) for High Altitude Reconnaissance Vehicle (HARVe) which can be launched from a missile. The power generation system is optimized subject to constraints on vehicle buoyancy and energy balance. Alam et al. [22] presented a methodology for conceptual design of a high altitude airship with an improved optimization process.

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By coupling with other optimizations, the methodology sizes the airship to obtain an optimal solution for some user-defined objective function. However, it was rare in these studies to discuss optimization design for a high altitude solar-powered lifting-body hybrid airship for different flight strategies.

This paper presents details of an optimization design and analyses for initial sizing of solar powered hybrid airship with different flight conditions. The rest of this paper include: a solar irradiance and the geometric photovoltaic array on multi-lobed configuration model is proposed. After introducing the mass distribution and the design process, an optimization method was used to search the optimum solution of the minimum total mass as an objective. Then the sensitivity analysis is established to research the effects of date and latitude on the optimal mass of hybrid airship. The obtained conclusions provide a valuable reference for the preliminary design of high altitude hybrid airship.

2. Conceptual design

2.1. Solar irradiance model

Ignoring the sky scattering and earth radiation, the solar irradiance I_0 at the stratospheric altitude can be calculated with:

$$I = I_0\left(\frac{1+e_0\cos\lambda_e}{1-e_0^2}\right)^2$$

where I_0 is the solar constant that has a value of 1367 W/m^2, e_0 is the orbital eccentricity, for earth $e_0 = 0.0016708$, the true anomaly λ_e is given by:

$$\lambda_e = \theta_{day} + 0.0344\sin(\theta_{day}) + 3.49\times10^{-4}\sin(2\theta_{day})$$

θ_{day} is the day angle of the sun and is given by:

$$\theta_{day} = 2\pi(N-n)/365.24$$

where N is the day number in a year which means $N = 1$ represents January 1st and $N = 365$ December 31st in a non-leap year.

And the sun radiation power density received by hybrid airship is:

$$P_{sun} = I\sin\beta$$

where solar altitude β, the angle between the vector pointing to the sun and its projection on horizontal plane is calculated by:

$$\sin\beta = \sin\theta\sin\varphi + \cos\theta\cos\varphi\cos\omega(t)$$

where θ is latitude, φ is declination angle:

$$\varphi = 23.45\pi\sin\left(\left(2\pi\times\frac{284+n}{365}\right)/180\right)$$

And the $\omega(t)$ is solar hour angle, t is the time of day.

$$\omega(t) = \pi - \pi t/12$$

3. Photovoltaic array model

As for conventional shape a double ellipsoid and a cylinder in the middle body to place the solar array, the multi-lobe shape can be considered as several conventional bodies paralleled with the photovoltaic array on the top surface as shown in Fig. 1.

Similar to conventional layout, the three portion of solar array are installed on the upper surface of lobes in symmetric form. Assuming the lobe is an ellipsoid shape, the curved envelope and solar panel can be described as a rotating surface. The equation is given by:

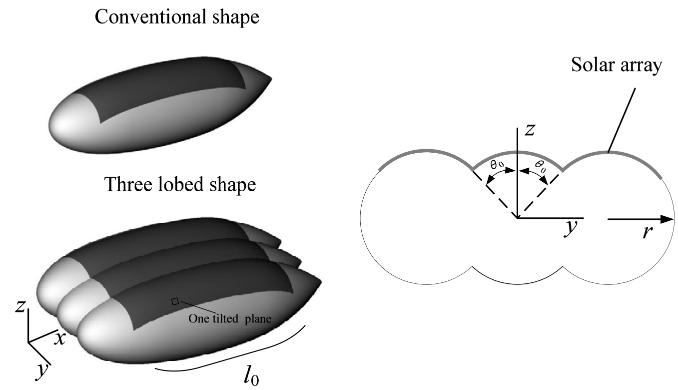

Fig. 1. Envelope and solar array configuration.

$$y^2 + z^2 = r^2(x) \quad 0 \le x \le L$$

Considering the sufficiently small grids as tilted planes instead of the curved surface of solar panels, the length of each section is dx along the direction of the rotation axis. And the width along the span can be represented as the length of small circular arcs along the circumferential direction. The area of tilted element ij is defined as A_{ij}, which can be described as [23,24]:

$$A_{ij} = rd\theta dx\sqrt{1+r'(x)^2}$$

where θ is the rotation angle along the circumferential direction.

To simplify the calculation model, assuming θ_0 is the central angle of solar array for each lobe and the solar array is only laying on the top surface, l_0 is the length of the solar array atop the hull, the total area of solar array can be expressed by:

$$A_{array} = N_L\sum_{y_i}\sum_{\theta_j}A_{ij}$$

where the N_L is the number of lobes.

In the inertial coordinate system, the unit vector of solar direct radiation $\vec{n}_s$ is a function of elevation angle and azimuth angle which can be expressed as:

$$\vec{n}_s = (\cos\theta_{ele}\cos\theta_{azi}, -\cos\theta_{ele}\sin\theta_{azi}, -\sin\theta_{ele})$$

While in the body reference frame, the incident solar radiation is changed with the different position on the panel attached to the envelope when the time is certain. Therefore, the solar direct radiation on the elements ij can be expressed by

$$q_{ij} = \alpha_{proj}\cdot I\cdot A_{ij}$$

where α_{proj} is the projection coefficient of solar direct radiation on the grid normal vector through a coordinate transformation. Assuming the azimuthal angle of the hybrid airship is zero, the average solar irradiance per unit area is calculated using MATLAB as shown in Fig. 2.

Considering the added mass of collector grid network and other auxiliary components, the mass of the solar array can be expressed as:

$$m_{panel} = \rho_{panel}S_{panel} = \frac{1}{2}\rho_{panel}\alpha S_{ref}R$$

where R is the ratio of the solar cell area atop the HA, α is a factor which is only relevant to the shape of hybrid airship.

3.1. Fuel cell model

Energy management monitors and controls the charge and discharge loops of the fuel-cells modules. Power conversion generates