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Multi-objective multidisciplinary design analyses and optimization of high altitude airships

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ABSTRACT

High Altitude Airships (HAAs) offer tremendous potential as long-endurance relocatable aerial platforms for several strategic and commercial applications. Design, analyses, and optimization of HAAs involves a complex interplay of various disciplines, and hence a multidisciplinary approach is essential. This paper describes a methodology to obtain the optimal design of an HAA meeting the requirements of onboard payload and power. The methodology couples six mutually interacting disciplines, viz., Environment, Geometry, Energy, Structure, Aerodynamics, and Thermal. The design problem is posed in a multidisciplinary optimization framework involving eleven design variables drawn from these six disciplines, and optimal solutions are obtained using Genetic Algorithm. The methodology obtains the optimal envelope shape, layout of the solar array, and altitude of operation, and determines the most critical day of operation. To demonstrate the efficacy of methodology, the optimal solutions are obtained for five different geographical locations of deployment, and compared with those for a standard envelope shape. A comparative study of these solutions is carried out to highlight the importance of thermal considerations in design optimization. Since the problem involves mutually conflicting disciplines; a multi-objective optimization involving Aerodynamics and Structures are also carried out. It is noticed that operating parameters and thermal behavior have a significant effect on design.

1. Introduction

High Altitude Airships (HAAs) are being proposed as buoyant aerial platforms to be deployed at altitudes between 17–25 km, where the ambient winds are low in magnitude. These stations are expected to act as a platform to mount the various devices related to surveillance and next-generation communication to facilitate the security and high-speed Internet connectivity. HAAs offer many advantages compared to satellites, viz., lower cost, quicker deployment, and their ability to be brought down, refurbished, and redeployed as and when needed. Such airships are to be deployed for long durations (several weeks or months at a time), the most practical means to address their power requirement is the use of a Solar Regenerative Fuel Cell (SRFC) system [1].

In an SRFC system (shown in Fig. 1), an adequate amount of solar arrays are mounted on the upper surface of the airship envelope. During daytime, the solar arrays generate enough power to meet the needs of onboard mounted payload and propulsive power. Excess power is used for electrolysis of water to generate Hydrogen and Oxygen, which are then stored onboard, and used to meet the power requirements during the night, or during lean periods [2].

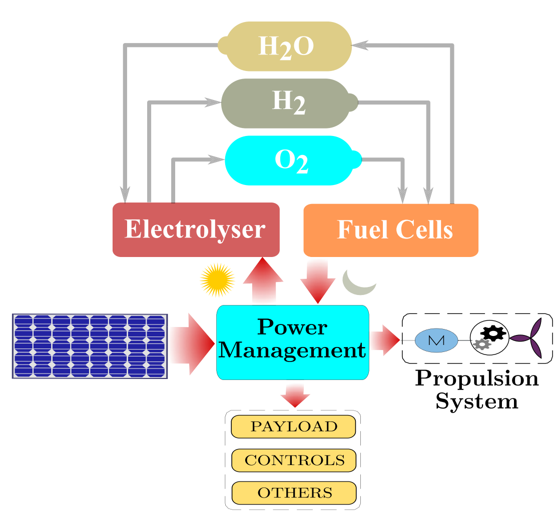

Fig. 1. Energy and propulsion system coupled with RFC.

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Nomenclature

A_{env}	Envelope surface area
A_{fin}	Fin surface area
A_{SA}	Area of solar array
a_i	Shape coefficient
B_F	Buoyancy force
$C_{DV,env}$	Envelope volumetric drag coefficient
$C_{DV,total}$	Total volumetric drag coefficient
C_p	Prismatic coefficient
D	Maximum diameter of airship
D_c	Equivalent diameter
D_{tot}	Total drag
$d\vec{A}$	Elementary area
$d\vec{b}$	Elementary width
dE	Energy generated from elementary area
$d\vec{l}$	Elementary length
E_{avl}	Total energy generated
E_{req}	Total energy required
h_{alt}	Altitude of deployment
I	Total incident solar radiation
I_D	Direct solar radiation
I_d	Diffused solar radiation
I_{day}	Day of design
L	Length of airship
M	Bending moment
M_{gas}	Molecular weight of LTA gas
M_{air}	Molecular weight of air
m	Location of maximum diameter
m_{ener}	Mass of energy system
m_{env}	Mass of envelope
m_{fin}	Mass of fins
m_{gas}	Mass of LTA gas
m_{misc}	Miscellaneous mass
m_{SC}	Mass of solar array
m_{strt}	Structural mass
m_{tot}	Total mass
$\hat{\boldsymbol{N}}$	Surface normal
$\hat{\boldsymbol{N}}_{\boldsymbol{s}}$	Unit vector along Sun ray
$\boldsymbol{R_s}$	Rotation matrix
P_{thrt}	Thrust power
P_{pay}	Power needed by payload
P_{cont}	Power needed by control system
P_{tot}	Total power
Re	Reynolds number
$\vec{r}$	Position vector
r_o	Nose radius
r_1	Tail radius
T	Temperature
T_{ref}	Reference temperature
t_{day}	Duration of day
t_{night}	Duration of night
V_{env}	Envelope volume
v	Wind speed
w_{thrt}	Power density of propulsion system
w_{rfc}	Energy density of RFC
Y_s	Starting location of solar array
Y_f	final location of solar array
Δt	Time interval
ΔH	Altitude difference in km
Δp	Total pressure difference
α	Solar elevation angle
β	Temperature coefficient
η_a	Packing area efficiency
η_c	Solar cell conversion efficiency
η_e	Electrical component efficiency
η_P	Propulsive efficiency
η_{conv}	Energy storage conversion efficiency
η_T	Temperature dependent efficiency
η_{ref}	Reference efficiency
ρ_a	Density of ambient air
ρ_{fab}	Area density of envelope fabric
θ	Angle between surface normal and Sun ray
ψ_i	Included angle of solar array
ψ	Solar azimuth angle
θ_z	Zenith angle
δ	Declination angle
Γ	True anomaly
σ_h	Circumferential stress
σ_l	Longitudinal stress
σ_v	von-Mises stress

2. Issues in design of HAAs

Design of HAAs are driven by mainly two requirements, viz., lift and power. A giant airship envelope filled with Lighter-Than-Air (LTA) gases provides the essential lifting required by the system at proposed operational altitude. A suboptimal solution during design optimization add to the system weight, which in turn need an extra lift. Higher lift requires a larger envelope, and therefore encounter additional drag which results in larger solar panels needed, which adds to more system weight, and so on. Moreover, magnitude of ambient winds, solar radiation availability, and the thermal response of the system vary over the calendar year and geographical location of deployment of an HAA.

The geographical location of deployment and the availability of solar radiation at the altitude of deployment play a very significant role in the size and configuration of the envelope and solar array of an HAA. There is also an interesting inter-disciplinary conflict that affects the value of some design parameters. For instance, the higher ambient wind is preferable to thermal considerations, as they help in lowering the temperature of solar arrays and hence maintaining high efficiencies. However, high ambient winds are not preferred from aerodynamic concerns, since they result in much higher Drag, and thus a significant increase in the power required. Therefore, a multidisciplinary design optimization and analyses methodology is essential to identify a truly optimum design.

The next section provides an overview of previous studies in design and optimization of HAAs, and brings out the need for the present study, by listing their shortcomings. Details of the methodology and six disciplinary models that are present in it are then provided. The next section explains how the optimization problem was formulated in a multi-disciplinary and multi-objective framework. This is followed by a description of the results obtained by coupling the methodology to a Genetic Algorithm (GA) for single objective and NSGA-II for multi-objective optimization.

3. Survey of literature

Wang and Shan [3] have carried out shape optimization of stratospheric airship, but the study was limited to a single discipline. Wang et al. [4,5] have carried out MDO based optimization of single composite objective function involving disciplines from Energy, Aerodynamics and Structure. However, their approach for

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