

Propulsion of Photovoltaic Cruiser-Feeder Airships Dimensioning by Constructal Design for Efficiency Method

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ABSTRACT

The European project MAAT (Multi-body Advanced Airship for Transport) is producing the design of a transportation system for transport of people and goods, based on the cruiser feeder concept. This project defined novel airship concepts capable of handling safer than in the past hydrogen as a buoyant gas. In particular, it has explored novel variable shape airship concepts, which presents also intrinsic energetic advantages. It has recently conducted to the definition of an innovative design method based on the constructal principle, which applies to large transport vehicles and allows performing an effective energetic optimization and an effective optimization for the specific mission. While the traditional constructal method performs an optimization with a down-to-top approach, it produces an optimization process in two stages: the first one defines the optimal characteristics of the system understood as a unitary system to achieve the desired performances; the second analyzes the subsystems, examining those most disadvantaged, in order to optimize its performance for the desired goal. It has been deeply tested on a traditional shaped airship allowing verifying that a changing volume airship has globally better energetic performances than a fixed volume one. This paper performs a preliminary analysis of the method for the design of a cruiser/feeder multibody airship such as the one, which is going to be designed inside the MAAT project. The model presented defines the guidelines for the optimization of the system considering the magnitudes involved in flight physics to achieve the goal of energetic self-sufficiency.

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INTRODUCTION

MAAT Project is an EU 7FP project related to the design of a cruiser/feeder airship system [1, 2]. This project derives from a preceding project called PSICHE regarding the analysis of the hypothesis of energy production in stratosphere by photovoltaic energy caption and conversion in hydrogen and oxygen. It requires a binary system composed by a high altitude airship platform and a feeder airship connecting it to the ground with capability of lifting up the necessary water for hydrolysis bringing down hydrogen and oxygen [3, 4, 5].

These projects have lead to a deep study about solar photovoltaic productivity at high altitude [6], which is necessary to ensure an adequate level of success to both projects. In particular, it has been demonstrated that photovoltaic energy caption at high altitude is about two

times the one on the ground, that photovoltaic productivity is further increased because of the lower temperature of equilibrium of PV modules. In addition, hydrogen and oxygen storage as both compressed gas and liquefied gas is higher than the production on the ground.

MAAT project allows defining a novel airship architecture, which can change its own volume during service to regulate the buoyant force and ensure an increased level of safety using hydrogen. This novel airship architecture does not include the presence of internal air ballonets, reducing the risks connected with hydrogen use as buoyant gas. Air ballonets do not ensure an adequate level of safety, especially during long airborne time missions [7]. The permeability of the envelope of the ballonets to hydrogen makes presents serious problems related to the possibility of reaching hydrogen auto-ignition conditions.

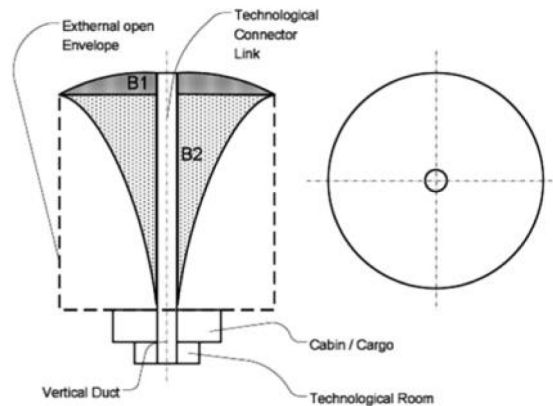


Figure 1. MAAT feeder conceptual design

Some energetic issues presented by the MAAT project, related in particular to the energetic design of the cruiser, which needs a large optimization process to ensure an effective energetic self-sufficiency ensuring adequate performances for transport needs. Energetic needs increases directly with system mass and volume, necessary to produce the necessary aerostatic force. Energetic production on the other side requires the largest possible area to maximize the photovoltaic caption.

A NOVEL DESIGN METHOD

The above-mentioned energetic issues forces to the definition of a novel design process, which allows this large optimization process. After a long bibliographic research on optimization and design methods, it has verified how the constructal principle could apply to an airship system. It has also observed that traditional optimization based on multidisciplinary optimization method [8, 9] does not produce adequate results on the specific problem concerning a breakthrough transport concept.

Adrian Bejan [10, 11] has defined constructal principle as follows: "For a finite-size system to persist in time (to live), it must evolve in such a way that it provides easier access to the imposed currents that flow through it."

Constructal method assumes that the design approach of a system can be analysed by dividing it into elementary parts and analysing the parts starting from the optimization of the most problematic with a down-to-top design approach.

This method cannot directly apply to the design of a complex transport vehicle using this down-to-top approach.

The effort of the authors has been the one to realize a deep study on constructal optimization methods to ensure an effective applicability to a large-scale innovative transport system characterized by an effective physical complexity and contradictory goals such as the ones expressed above.

A novel design method considers two separated steps. The first is a top-to down process, which involves a correct conceptual optimization of the system as a whole and of its subsystem based on the desired goals fixed for the full system. The second consists in an effective constructal

optimization of the subsystem which allows to reach the specific goals needed by the project and, if the could not be reached to define the possible solution which is the nearest one to the ideal that has been previously defined. This methodology has been tested with surprisingly results to the design of a traditional airship (with the same specifications of current commercial transport one). The results allows to define a system subject with an almost constant drag force with altitude and have permitted to test that the previously obtained results about a variable shape airship were adequate [12, 13].

This method is named Constructal Design for Efficiency. It allows redefining the constructal principle in more complete way than ever done before: "a complex system can meet optimal performances if it has been optimized as a whole, defining the ideal performance required by its subsystems and they are then specifically optimized to approach as much as possible the predefined goals".

The results encourage applying the same method also to the full MAAT system. In this paper, a preliminary model has been then applied and verified.

AIRSHIP MODEL

Airships can be divided into two different categories: pressurized or rigid. Pressurized models are much lighter than rigid because the have no structure and the hull is maintained by a differential pressure between the internal lifting gas and the external atmosphere. Pressure airships are sometimes made "semi-rigid" by adding a structural keel to share the loads generated by aerodynamic forces [14].

Due to the necessity of reducing the masses, it has been assumed that the airships have a pressurized hull. It has been assumed that the feeder can act vertically as an aerostatic balloon and the cruiser must remain airborne for long times. The equations of the airship are reported below.

Atmospheric Model

Atmosphere model are a fundamental part of the airship volume. Assuming Standard Atmosphere model it can be used the data in [table 1](#).

Table 1. Atmosphere data

Height - h - (m)	Temperature - T - (K)	Pressure - p - (Pa)	Density - ρ - (kg/m ³)	Cinematic Viscosity - ν - x 10 ⁻⁵ (m ² /s)
0	288.15	101325	1.225	1.46
2000	275.2	79500	1.007	1.72
4000	262.2	61660	0.819	2.03
6000	249.2	47220	0.660	2.42
8000	236.2	35650	0.526	2.90
10000	223.3	26500	0.414	3.53
12000	216.7	19400	0.312	4.56
13000	216.7	16580	0.267	5.33
14000	216.7	14170	0.228	6.24
15000	216.7	12110	0.195	7.30
16000	216.7	10350	0.166	8.54
17000	216.7	8850	0.142	9.99

Airship Hull Sizing

Airship hull can be sized by considering buoyant force:

$$M_{tot} = M_s + M_p + M_b + M_e + M_c \quad (1)$$

The volume of gas V_g and the density of both air (pair) and buoyant gas (ρ_g) depend on the altitude and temperature. The Volume at any specific altitude is assumed

$$V_g(h) = \frac{M_{tot}}{\rho_{air}(h) - \rho_g(h)} \quad (2)$$

Assuming the volume V_{max} at the maximum operative ceiling h_{max} equation (2) becomes:

$$V_{g,max} = V_g(h_{max}) = \frac{M_{tot}}{\rho_{air}(h_{max}) - \rho_g(h_{max})} \quad (3)$$

The payload of the system is composed by five different terms, which are shown in the below equation(4):

$$M_{tot} = M_s + M_p + M_b + M_e + M_c \quad (4)$$

where M_{tot} is the total payload, M_s is the mass of the structure, M_b of the balloons, M_p of the propulsive system, M_e of the energy system and M_c is the commercial payload.

This equation works properly for any airship system even if it assumes negligible the volume of the cabin if compared to the volume of the airship.

In particular, it is necessary to consider that some terms in the equation are dependent:

$$\rho_g(h) = f(\rho_{air}(h)), \quad (5)$$

because, the internal pressure is equal to the external pressure plus a term which ensures the capability of maintaining the shape.

It can be also assumed that M_b is a function of the balloon in the hypothesis that the airship has no internal balloons but varies external volume.

$$M_b = \rho_b \cdot A_b = \rho_b \cdot A_b(V_b) \quad (6)$$

Balloon dimensioning

The considered airship system has been designed as a pressurized one. The internal pressure of the balloon is the one that equilibrates the maximum aerodynamic pressure of the balloon, which has assumed equal to the pressure of the wind on a flat plane:

$$p_{aero} = \frac{1}{2} \cdot \rho_{air}(h) \cdot u_{max}^2 \quad (7)$$

where u_{ref} is the reference velocity equal to any arbitrary velocity greater than the maximum cruise speed u_{max} . Assuming for example a very conservative reference velocity of 100 m/s, it can be evaluated the internal pressure at various altitudes together with other internal parameters making the hypothesis of a balloon isothermal with external atmosphere.

Buoyant gas properties are reported in Table 2.

Table 2. Buoyant gas properties

Height - h - (m)	Temperature - T - (K)	Pressure - p - (Pa)	Differential pressure - Δp - (Pa)	Density - ρ - (kg/m ³)	Differential Density - Δρ - (kg/m ³)
0	288.1	107450	6125	0.09533	1.1297
2000	275.2	84533	5033	0.07834	0.9282
4000	262.2	65757	4097	0.06377	0.7556
6000	249.2	50521	3301	0.05138	0.6088
8000	236.2	38279	2629	0.04092	0.4849
10000	223.3	28568	2068	0.03218	0.3814
12000	216.7	20959	1559	0.02427	0.2876
13000	216.7	17913	1333	0.02074	0.2458
14000	216.7	15309	1139	0.01773	0.2101
15000	216.7	13084	974	0.01516	0.1796
16000	216.7	11182	832	0.01296	0.1535
17000	216.7	9562	712	0.01108	0.1313
18000	216.7	8173	608	0.00947	0.1122
19000	216.7	6987	520	0.00809	0.0959
20000	216.7	5974	445	0.00692	0.0820

The balloon has dimensioned considering it as a low thickness envelope pressurized in this case assuming the following expression, which applies to spherical recipients:

$$\sigma_f = \frac{p \cdot r}{2 \cdot t} \quad (8)$$

Fabric strength is classified on bias tensile strength, which can be evaluated in different directions depending on the directions of fibres inside the tissue. If k , the ratio of frontal

area and volume elevated at $2/3$, is the coefficient of the balloon, for a variable volume airship

$$k(h) = \frac{A(h)}{V^{2/3}(h)}, \quad (9)$$

the mass of fabric for balloon realization balloon is

$$M_b = \rho_b \cdot k(h) \cdot V^{2/3} \quad (10)$$

Equation (10) is the mass for the balloon. This represents the mass available for the internal structure and all systems. It varies with the fabric density and k . The required mass of buoyant gas becomes:

$$M_g = \rho_g \cdot V_{g,\max}$$

Drag and Power Estimation

By the size of the airship defined by equation (2), it is possible to calculate the expected drag force acting on the airship:

$$D = \frac{1}{2} \cdot \rho_H \cdot u^2 \cdot A_f \cdot C_{D,A} = \frac{1}{2} \cdot \rho_H \cdot u^2 \cdot V^{2/3} \cdot C_{D,V} \quad (11)$$

Power needed for propulsions at constant velocity u has estimated by equation (12):

$$P_p = D \cdot u = \frac{1}{2} \cdot C_{D,A} \rho_H A_f \cdot u^3 = \frac{1}{2} \cdot C_{D,V} \rho_H V^{2/3} \cdot u^3 \quad (12)$$

The required power by propulsion system is given by (13):

$$P_{p,\text{eff}} = \frac{D \cdot u}{\eta_p} \quad (13)$$

where η_p is the propulsive efficiency. Assuming the actuator disk theory it can be expressed as the ratio between the power imparted to the fluid and the power consumed for propulsion:

$$\eta_p = \frac{P_{\text{fluid}}}{P_{\text{prop}}} = \frac{2 \cdot u_c}{u_c - u_0} \quad (14)$$

In particular, it has assumed u_c the velocity of the fluid exiting the propeller and u_0 the velocity of the vehicle. Assuming a uniform motion, the thrust is equal to drag (15):

$$T = D = \dot{m} \cdot (u_c - u_0) \quad (15)$$

It can be also evaluated the energy required for the advancement during 24 hours:

$$E_{\text{day}} = D \cdot u_{av} \cdot 24 \quad (16)$$

where u_{av} is the average velocity during the day.

On annual basis, it becomes:

$$E_{\text{year}} = D \cdot u_{av} \cdot 8760 \quad (16')$$

Assuming m_p the unitary weight for kW of the propulsive system it can be evaluated also the mass M_p of the propulsive power by (17):

$$M_p = m_p \cdot P_p \quad (17)$$

Photovoltaic Energy Production

Another fundamental system parameter is the photovoltaic energy production. It has simply expressed assuming the overall efficiency of the photovoltaic plant η_{PV} and the efficiency of the energy storage and conversion equipments η_E . The amount of useful photovoltaic power is given by (18):

$$P_{PV}(t) = S_{PV} \cdot I_{sol}(t) \cdot \eta_{PV} \cdot \eta_E \quad (18)$$

The amount of energy produced had determined by considering the number of hours of useful photovoltaic production per day:

$$E_{PV}(t) = \eta_{PV} \cdot \eta_E \cdot S_{PV} \cdot I_{sol}(t, h) \cdot t_{sol} \quad (19)$$

where t_{sol} is the effective amount of hours with sunshine. On annual basis, it becomes:

$$E_{PV,\text{year}}(t) = \eta_{PV} \cdot \eta_E \cdot S_{PV} \cdot I_{sol}(t, h) \cdot t_{sol,av} \cdot 365 \quad (19')$$

Equalling (19) and (16') it is possible to calculate the necessary area and mass of photovoltaic system.

$$S_{PV} = \frac{D \cdot u_{av} \cdot 24}{\eta_{PV} \cdot \eta_E \cdot I_{sol}(t, h) \cdot t_{sol,av}} \quad (20)$$

and

$$M_{PV} = S_{PV} \cdot m_{PV} = \frac{D \cdot u_{av} \cdot 24}{\eta_{PV} \cdot \eta_E \cdot I_{sol}(t, h) \cdot t_{sol,av}} \cdot m_{PV}, \quad (21)$$

where m_{PV} is the unitary mass of the PV plant per square meter.

DESIGN SPECIFICATIONS

In this paper, the full MAAT cruiser-feeder [7] system has been defined and optimized for the specific mission defining also in different possible configurations.

The feeder has to minimize its own energetic consumption during take-off and landing operations and