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Engineering Notes

Multidisciplinary Shape Optimization of Aerostat Envelopes

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Nomenclature

a_n	=	coefficient for parabolic rear shape
$a_1, a_2, b_1, b_2, c_1, c_2, d_1, d_2$	=	coefficients of cubic splines that parameterize the center portion of the envelope
C_D	=	drag coefficient
d	=	envelope diameter
l	=	envelope length
n_ν	=	load per unit length along meridians, i.e., in warp direction
n_φ	=	load per unit length along latitude circles, i.e., in weft direction
p_R	=	internal overpressure in the aerostat envelope
R	=	radius of curvature of spherical front portion of envelope
R_1, R_2	=	radii of curvature and transverse curvature of an inflated structure
X_D	=	design vector for shape optimization

I. Introduction

AIRSHIPS and aerostats belong to the family of lighter-than-air (LTA) systems, in which the force of buoyancy acting on a large envelope filled with the LTA gas comprises the major component of the lift force. Whereas an airship is a free-flying vehicle with a propulsive device and multi-axis control system, an aerostat is a tethered platform, with adequately sized fins to provide stability.

The principal component of an airship or aerostat is the envelope, which is usually a body of revolution. Past studies on shape optimization of airships [1–3] have looked at the envelope in isolation and have focused only on envelope drag reduction. An aerostat, however, is primarily a payload-carrying platform; hence, the most important performance parameter is its payload-carrying capacity under the specified operating conditions for a given envelope volume.

II. Effect of Envelope Shape on Aerostat's Payload Capacity

The envelope shape affects its payload-carrying capacity in many ways. The envelope weight is a function of its surface area, which can vary greatly with its shape for a given volume. The difference in internal and external pressures on the envelope generates stress on the membrane, and for a given internal pressure difference, the stress is a function of the envelope shape. Thus, the shape of an envelope directly influences its self-weight. The envelope shape also affects the aerodynamic force and moments generated on it. The size of fins required to trim the aerostat and to provide the required stability is also a function of its shape. The ambient wind on the aerostat produces drag, which tends to displace it along the direction of flow. This displacement is called *blow-by*, and it reduces the operational height of an aerostat; a longer tether will have to be released to maintain the specified altitude of operation, at the expense of a decrease in payload capacity.

The present study attempts to address the problem of envelope shape optimization from a multidisciplinary perspective and is an extension of previous work by Kanikdale et al. [4], involving a weighted composite objective function incorporating drag, hoop stress, and self-weight of an aerostat's envelope. A methodology has been developed that, for a given envelope shape, can estimate the payload capacity of an aerostat, keeping its volume fixed. This methodology takes into account several factors such as aerodynamic forces and moments acting on the envelope, stability and trim requirements from the fins, and the stresses developed in the fabric (factors typically coming under the purview of different disciplines) for estimation of payload capacity, which is maximized through shape optimization.

III. GNVR Envelope Shape

One of the frequently used methods of shape optimization is expressing the body profile as a combination of simple geometric shapes. One such standard shape is the GNVR shape, named after G. N. V. Rao of the Indian Institute of Science, who developed it. The profile of the GNVR shape is a combination of an ellipse, circle, and parabola, as shown in Fig. 1. The front portion of this shape has an elliptical profile, which allows an easy interfacing with the mooring system, and the rear parabolic shape ensures ease in attachment of the fins.

The entire geometry of GNVR shape is parameterized in terms of its maximum diameter, as shown in Fig. 1. Computational [5] and experimental [6] studies have indicated that this shape corresponds to low C_D for aerostats operating at $M = 0.1$ and $H = 1.0$ km; hence, it was chosen as a baseline for comparison purposes.

IV. Description of the Methodology

The first step in the methodology is to parameterize the envelope geometry in terms of certain shape-related parameters. This is followed by the determination of the aerodynamic and buoyancy forces acting on the envelope, profile of the tether, self-weight of the envelope, and the size (and hence weight) of the fins required to ensure adequate stability. The payload capacity of the aerostat is the net difference between the upward forces (viz., buoyancy and aerodynamic lift) and downward forces (viz., self-weight of the aerostat and the weight of tether required). The methodology was then coupled to an optimization algorithm to determine the shape that results in maximum payload capacity for a given envelope volume.

The various steps in the methodology are explained in the sections that follow.

A. Parameterization of Envelope Geometry

The envelope geometry of a generic aerostat was parameterized in the form of a section of a sphere for the nose, two cubic splines for the midbody, and a parabola for the rear, as shown in Fig. 2.

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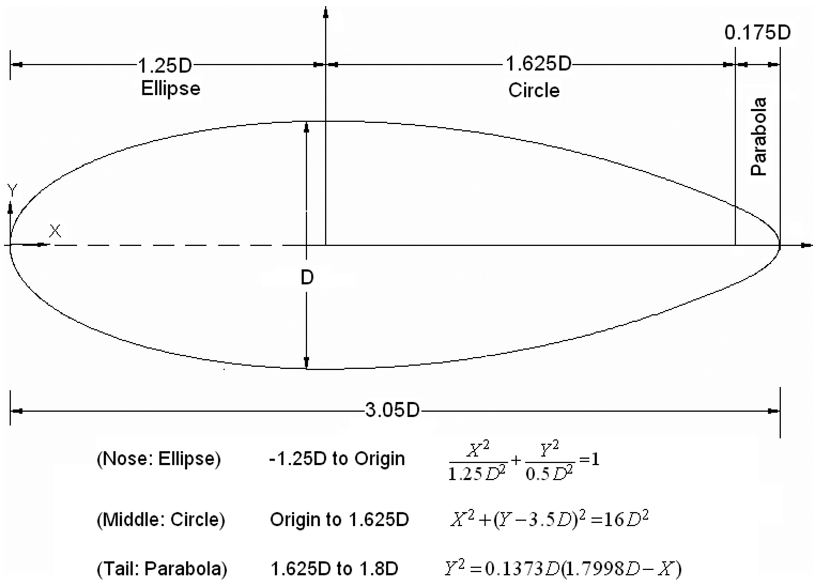

Fig. 1 GNVR shape with geometry parameterized in terms of maximum diameter.

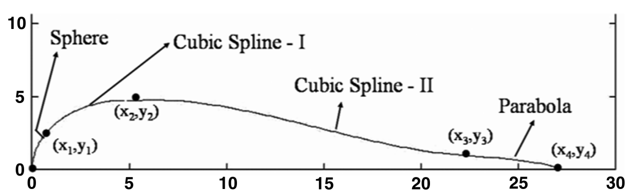

Fig. 2 Parameterization of geometry.

Sphere (circle in 2-D):

$$y^2 = 2xR - x^2 \tag{1}$$

Spline I:

$$y = a_1x^3 + b_1x^2 + c_1x + d_1 \tag{2}$$

Spline II:

$$y = a_2x^3 + b_2x^2 + c_2x + d_2 \tag{3}$$

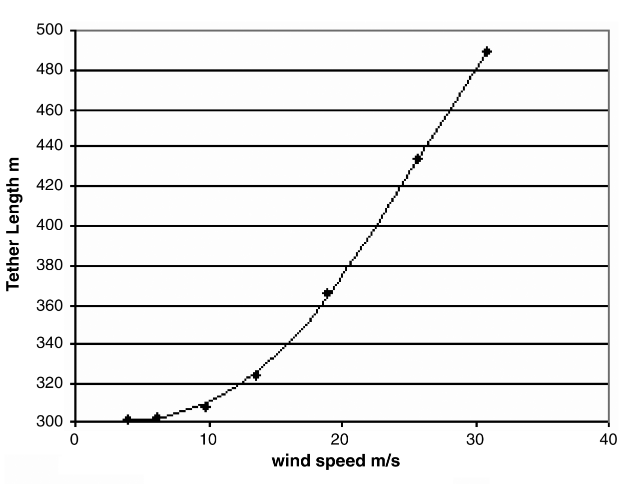

Fig. 3 Validation of algorithm for tether profile estimation.

Parabola:

$$y^2 = a_n(x_4 - x) \tag{4}$$

By imposing constraints on the slope continuity at points (x_1, y_1), (x_2, y_2), and (x_3, y_3) and zero slope at point (x_2, y_2) for an aerostat envelope of fixed volume, a six-component design vector is obtained, as listed in Eq. (5):

$$X_D = (x_1, y_2, x_2, x_3, y_3, x_4) \tag{5}$$

Additional constraints on the radius of curvature and rate of change of slope were also employed to incorporate manufacturing constraints. A shape generation algorithm was developed, which generated various possible shapes of aerostat envelopes by varying these geometrical parameters, while meeting the specified constraints.

B. Tether Profile Determination

An iterative method is used to calculate the tether force and payload capacity of the aerostat. A high value of payload is assumed as a starting value, and the tether profile is estimated using the methodology suggested by Wright [7]. If the results indicate that the net lift is insufficient to lift the required length of tether, the assumed value of payload is incrementally reduced till a feasible solution for the tether profile is obtained. Aerodynamic forces acting on the envelope and fin are estimated using the semi-empirical formulas

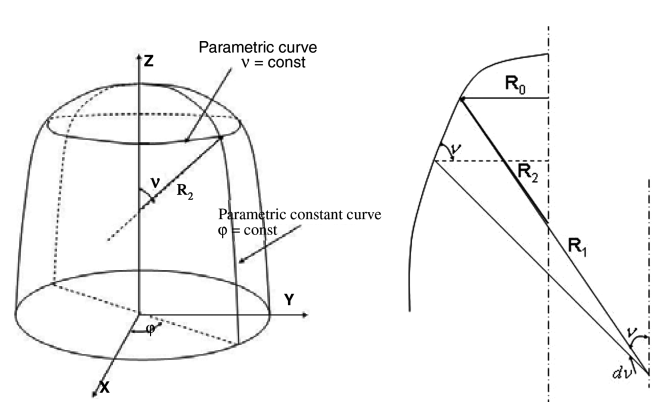

Fig. 4 Coordinate system for axisymmetric bodies [10].

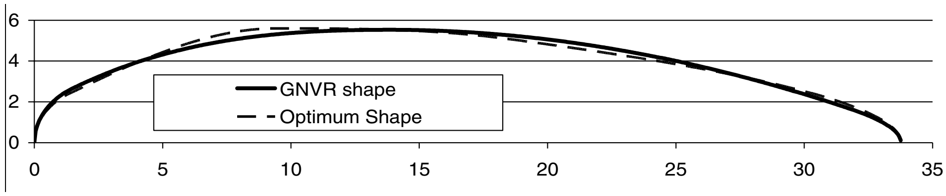

Fig. 5 Comparison of the profile of GNVR and optimum shape.

listed by Jones and DeLaurier [8]. To eliminate the need for using a flow solver for determination of C_D in each iteration step of the optimization loop, a response surface developed by Kale et al. [9] for C_D as a function of envelope length l and six geometrical parameters listed in Eq. (1) are employed.

The methodology for tether profile development was validated against experimental data for an aerostat with envelope volume of 250 m^3, as shown in Fig. 3.

C. Estimation of Weight of Envelope

The weight of the envelope is estimated as a function of the weight of the envelope fabric, The weight of the envelope fabric depends on the surface area of the aerostat and the specific density of the envelope material. The material used for the construction of the envelope should be strong enough to withstand the loads developed due to the internal pressure of the gas inside the aerostat and the dynamic loads imposed by the ambient wind.

The hoop and bending stress developed in the envelope using the approach suggested by Otto [10] for an axisymmetric body of revolution, with the coordinate system shown in Fig. 4. The force per unit length in the warp υ and weft φ directions due to internal pressure p_R can be estimated using Eqs. (6) and (7) as

$$n_\nu = \frac{p_R R_2}{2} \tag{6}$$

$$n_\varphi = p_R R_2 \left[1 - \frac{R_2}{2R_1}\right] \tag{7}$$

For the aerostat shape to be free of kinks after it has been inflated, n_φ and n_ν should be positive or tensile at all points, and n_υ is essentially positive at all points if the aerostat is inflated, since p_R and R_2 are both nonzero and positive. However, n_φ can have negative values; hence, the condition for the load to be tensile at any point is that $R_2 < 2R_1$ at that point, as shown by Eq. (7). If this condition is not satisfied, the membrane is not stretched and the aerostat may develop a fold or a kink in that region.

D. Estimation of Fin Size

Fins are required for the stability of the aerostat, and they also constitute a major portion of the weight and add to the drag. To accurately estimate the payload capacity of the aerostat, the size and weight of the fins that would be required for adequate stability are estimated. An inverted Y configuration is selected for the fins so that rain and snow falling on the fins do not accumulate at the fin root junction, thus avoiding disturbance to the balance of the aerostat.

Table 1 Weight breakup of aerostat with GNVR and optimum profile

Profile	Payload, kg	Envelope, kg	Fin, kg
GNVR	237.4	309.4	107.8
Optimum	242.5	310.5	102.1
% change	2.15	0.36	−5.29

Using the approach by Krishnamurthy and Panda [11] for equilibrium analysis of aerostats, the location of the confluence point‡ of an aerostat can be determined, such that angle of attack remains constant with change in velocity. Although it is essential that the size of the fins should allow the confluence point to be present outside the aerostat, it is also desired to locate it at a convenient distance behind the nose and below the axis of the aerostat. An iterative methodology for fin sizing was developed, wherein for an assumed value of aspect ratio and taper ratio of the fin, the area of the fin is determined such that the confluence point is at the desired location and the stability margin§ is more negative than a desired value. Semi-empirical correlations for envelope-fin mutual interference factors and crossflow drag coefficients listed by Jones and DeLaurier [8] for symmetric fin configuration were corrected for unsymmetric Y-fin configuration, as suggested by Gill et al. [12], and used in the methodology.

E. Optimization Technique Employed

The methodology for payload estimation was coupled to an optimization code based on genetic algorithms named GADO (Genetic Algorithm for Design Optimization) developed by Rasheed [13]. The code has several features that make it ideally suited for solving complex engineering design problem, e.g., a guided crossover operator, which gives a gradientlike function to this code. Although “greedy” in nature, this operator quickens convergence in the later stages of the optimization. Other useful features of the code include a screening module that saves computational time, a diversity maintenance module that prevents premature convergence, and some new types of crossover operators. Details of these features and other information about GADO can be obtained from [13].

V. Results

The methodology was applied for optimization of envelope shape of an aerostat of volume of 2000 m^3, and the payload capacity was obtained. For comparison purposes, the payload capacity of GNVR profile (Fig. 1) was also obtained. Table 1 lists the weight breakup of the major components of the two aerostats.

It is seen that the use of optimum shape leads to an increase of ≈5 kg in the payload-carrying capacity. This improvement primarily results from requirement of a smaller fin. A comparison of the GNVR and optimum profile is shown in Fig. 5. It can be seen that both the shapes are quite similar and differ only at some locations.

VI. Conclusions

The methodology described in this paper can be used for arriving at the optimum shape of the envelope of an aerostat that maximizes its payload, while incorporating considerations aerodynamics, structures, and flight mechanics. A semi-empirical method is used for the estimation of aerodynamic loads, and envelope drag coefficient at zero angle of attack is determined using a response-surface method. Sizing of the fins is carried out ensuring a specified level of stability in specified ambient wind conditions. The tether profile, and hence its self-weight, is estimated to incorporate the effect of drag on the

‡Confluence point is the location at which the main tether is attached to the aerostat envelope.

§The stability margin of an aerostat can be defined as the rate of change of moment coefficient with change in angle of attack.

payload capacity of the aerostat due to *blow-by*. A constraint is introduced to avoid appearance of kinks and folds in the shape. Optimum shape and fin size are generated by coupling the shape generation algorithm and a GA-based optimizer. For an aerostat of 2000 m^3 envelope volume, shape optimization using the methodology outlined in this paper resulted in 2.15% improvement in payload capacity, compared to an aerostat of a standard GNVR shape. This improvement is expected to be larger for aerostats of higher envelope volumes, since it is a known fact that the payload capacity increases nonlinearly with the increase in envelope volume.

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