Multidisciplinary Shape Optimization of Aerostat Envelopes

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Introduction

Aerostat is an aerodynamically shaped tethered body, belonging to the family of Lighter Than Air (LTA) vehicles. Aerostat envelopes are filled with a LTA gas (which is Helium or Hydrogen in most cases) and thus generate lift due to buoyancy, which is used to raise a given payload to a certain height. The aerodynamically shaped envelope has least drag when it is aligned with the direction of wind. Hence, adequately sized fins have to be provided on the envelope to impart it stability during wind disturbances. The tether load is distributed across the several points along the length of the envelope through ropes called confluence lines to avoid excessive load on the membrane at a single point. The confluence lines are joined with the tether at the confluence point through a pivot which allows the aerostat to rotate freely and align with the direction of the wind.

Payloads in modern day aerostats are usually radars, surveillance cameras or communication equipment. In order to deploy more sophisticated equipment on aerostats, it is always desirable to increase their payload capacity, without compromising on their operating altitude. The envelope shape affects the payload capacity of an aerostat in several ways. This paper discusses an MDO approach for identifying the shape of an aerostat envelope that results in the largest payload capacity for a given envelope volume.

Effect of envelope shape on payload capacity

The envelope shape affects the payload capacity in the following ways

1)**Surface Area**: The envelope weight is decided by the Total Surface Area (TSA) of the envelope.

$$W_{env}=TSA*\rho_{matl}$$

where

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ρ_{matl} = density of the envelope material

For a fixed volume, the surface area varies greatly with the shape. It is widely known that the minimum surface area for a given volume is obtained for a spherical shape.

2)**Envelope Stress :** The difference in internal and external pressure on the aerostat envelope generates stress on the membrane. For a given pressure difference, the stress is a function of the envelope shape. If the stress is low, a material of low ultimate strength which is expected to be lighter can be used. On the other hand for a higher stress, a stronger material which is expected to be heavier (higher ρ_{matl}) will have to be used to make the envelop. Thus shape directly influences the self weight of the aerostat.

3)**Fin Weight:** The envelope shape decides the aerodynamic force and moments generated on the envelope. The size of fins required to trim the aerostat at a given angle of attack and to provide the required stability is thus decided by the shape of the aerostat.

4)**Tether weight:** The effect of shape on drag has been well established through past studies[1]. Drag causes blowby on the aerostat causing it to draw a longer tether for the same height of operation. Thus the weight of the tether supported by the aerostat increases for a shape causing higher drag. This additional tether weight is carried at the expense of useful payload weight. To increase the payload capacity, it is thus necessary to reduce the drag on the aerostat.

The problem is thus multidisciplinary in nature involving structures (in terms of fabric stresses), aerodynamics (in terms of drag) and flight dynamics(in terms of trim angle and stability).

Parameterization of Envelope Shape

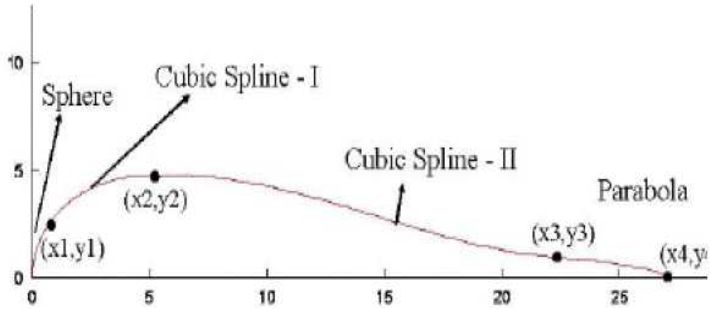

Figure 1Parameterization of Shape

Kanikdale et al [2] proposed a shape generation algorithm for airship bodies where the envelope is modeled as a body of revolution of a compound profile made up of 4 curves. The constituent curves in the profile are i) an arc of a circle for the nose (spherical in 3D) ii) two cubic splines for the mid-body and iii) a parabola for the rear. The circular/spherical nose region was a constraint arising out of the spherical mooring masts that are in use. The rear was selected to be parabolic to make it amenable to fit fins. On applying suitable constraints for geometric and slope continuity at the intersection of the different curves, the entire profile can be expressed in terms of 6 design variables – x_1, x_2, y_2, x_3, y_3, y_4. The same algorithm is used in the present work.

Problem Definition

The problem is defined as

Maximize Payload = $F(x_1, x_2, y_2, x_3, y_3, y_4)$

Subject to

Volume = 2000 m3

Operating height = 1000 m

Angle of Attack = 2.25^0

Static Margin <= -0.2

maximum stress σ_{max} < breaking load of material

Drag and blow-by

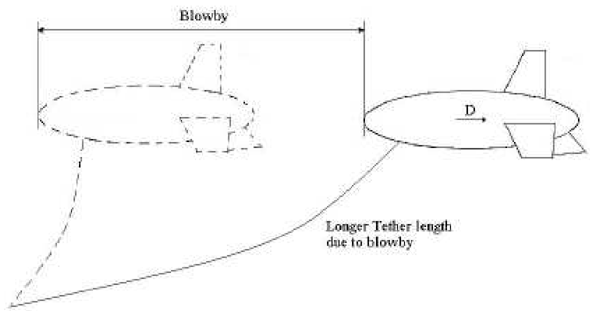

Figure 2 Blow-by

The ambient wind on the aerostat produces drag which tends to displace it along the direction of flow. This displacement is called blow-by. Blow-by reduces operational height and may also give rise to functional disadvantages depending on the application eg:- it produce errors in station keeping. To maintain the height of operation, a longer tether will have to be released at the expense of a decrease in payload capacity. Therefore a low coefficient of drag is an essential requirement of an aerostat envelope. The necessity of low drag also places demands on the trim angle and stability margin of the aerostat. Since C_D increases with angle of attack, it is essential to keep the angle of attack for the aerostat as low as possible. It is also necessary to keep the static margin high so that the aerostat shows quick response to wind disturbances and the angle of attack is maintained.

Estimation of Envelope Drag

With the help of the shape generation algorithm, around 600 feasible shapes were generated, and their C_D values were obtained using the FLUENT™ CFD code. An axi-symmetric grid was built around the upper half of the body in the semicircular computational domain, and an axi-symmetric segregated implicit solver was selected, in conjunction with S-A turbulence model. The required boundary condition parameters i.e., pressure, temperature and density were obtained using ISA conditions corresponding to altitude of 1.2 Km. Sutherland's formula was selected for viscosity variation with temperature. The pressure distribution and C_D were obtained for a Gauge Pressure of 87514 Pa, and Mach No. of 0.107.

The effect of the 6 design variables on C_D was studied and it was found that the position of maximum diameter x_2 had a significant role on the drag. Aerostat shapes were classified into three distinct regimes based on the position of maximum diameter and a separate response surface was fit for each of these regimes. Further details of the study can be obtained in reference [3]

Estimation of Aerodynamic Coefficients of the Envelope

Jones and DeLaurier[4] have suggested a semi-empirical method to determine the coefficient of Normal force C_z, Axial force C_x and moment about nose C_{M_nose} for a symmetric fin configuration. Gill et al.[5] have suggested a correction for fin dihedral in the inverted Y configuration. This method is used for calculation of the aerodynamic force and moment Coefficients.

Tether Profile Estimation

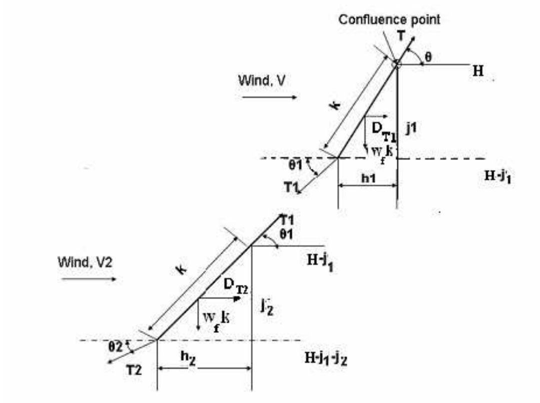

Figure 3 Tether Profile Estimation

To accurately estimate the payload capacity of the aerostat, it is necessary to determine the weight of the tether carried by the aerostat. An algorithm for determination of blowby of the aerostat and tether profile estimation, given the tether tension and the tether angle at the confluence point has been developed by Wright [6]. In this method, the tether is discretized into elements of equal lengths and starting from the confluence point, the tension and inclination angle of each subsequent element below is determined by solving for the equilibrium of forces. If at any point the tension or the inclination becomes zero it indicates that the vertical force is not sufficient to carry the weight of the tether .

The tension T and angle θ at the confluence point are obtained from the equations for equilibrium for the entire aerostat.

$T \sin\theta = B - W$

$T \cos\theta = D$

Methodology for sizing of fins an Aerostat

Fins are required for the stability of the aerostat, but they also constitute a major portion of the weight and also add to the drag. In order 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. A methodology for sizing the inverted Y- shaped fins of a tethered aerostat has been developed, in which the stability analysis is based on the approach suggested Krishnamurthy & Panda [7]. An inverted Y configuration is selected for the fins so that rain and snow falling on the fins does not accumulate on the fins thus avoiding disturbance to the balance of the aerostat. The coordinates of the confluence point for a given size of fin can be obtained and thus the stability margin $C_{M\alpha}$ taken about the confluence point can be obtained. The aspect ratio, taper ratio and location of the fin along the hull are initially assumed. The fin area required for adequate stability is determined through an iterative process. Starting from an initial small guess value, the fin area is increased till the confluence point is at an acceptable location. If the aerostat has sufficient static margin for the given fin size and confluence point, it is accepted.

Structural analysis

Otto [8] gives equations to determine force per unit length due to internal pressure for axisymmetric bodies. These are used to calculate the membrane loads on the basis of which, the envelop material is selected. For some aerostat profiles, the stress in some regions may also be compressive due to which folds or kinks develop in them. Such aerostat profiles are eliminated as folds and kinks would cause increased drag on the aerostat.

Methodology of Solution

Shapes are generated using Kanikdale's[2] shape generation algorithm, for various feasible combinations of the six variables which are used to parameterize the shape. Once the shape is known, the surface area and the load at various points on the envelope can be determined.

Hence the material to be used for fabricating the envelope can be decided upon and the fabric weight (W_{hull_fabric}) of the aerostat can be determined. The fin sizes as well as the tether weight depend on the payload carried by the aerostat. However, the payload is unknown and is in fact the quantity which we are interested to determine. Hence further analysis is through an iterative process. An initial high value of payload is assumed. For the estimated payload, the location of the center of gravity of the aerostat, the aerodynamic coefficients, and the weight of fins of the aerostat are calculated. Tether profile calculations are now carried out to determine if the available lift is sufficient to support the weight of tether required for the aerostat to operate at the given height and wind speed. If the available lift is not enough to support the tether, a lower payload is assumed for the next guess value and the process is carried out iteratively till a feasible configuration is achieved. Thus, given the six design variables the payload capacity of the aerostat can be determined. A Genetic Algorithm code GADO[9] is used to find the most optimum combination of the six design variables which specify the shape of the aerostat envelope to achieve maximum payload capacity of the aerostat envelope.

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