The Aerodynamic Performance of an Inflatable Wing in Aircraft

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Abstract. This paper explores the aerodynamic performance of an inflatable wing in aircraft using both theoretical and experimental methods. The theoretical analysis is based on inflatable structures and the existing simple pressure vessel equations for the necessary structural analysis. The present work also conducted more detailed aerodynamic analyses of inflatable wing, and in particular considers the trends for coefficients of lift and coefficients of drag, which help to understand with the varying airfoils angle of attack in predicted the lift to drag ratio behavior.

Introduction

In addition to morphing-wing aircraft and deployable-wing aircraft, inflatable-wing aircraft were also investigated. While inflatable-wing aircraft may seem to be a lesser-known technology than others, it has been in development for decade. Inflatable wing aircraft have been successfully demonstrated as early as the 1950's with the Goodyear Inflatoplane Model GA-468 [1]. The inflatoplane was designed and built in 12 weeks, with the goal of being a rescue plane that would be air-dropped behind enemy lines. The inflatable wing took about five minutes to inflate. The pilot would then hand-start the engine, and take off from a turf runway, requiring only 250 feet before the plane was off the ground. Several models were made, ranging from a single capacity, to two-person capacity aircraft, each with a 28 foot inflatable wing.

Inflatable wing was developed and integrated in aircraft design decades ago[2-4], including the development of lighter-than-air (LTA) vehicles, manned inflatable heavier-than-air vehicles and UAVs. While LTA vehicles also include inflatable structures, our main focus herein is on the inflatable wing used solely for lift generation. Inflatable wings are a promising method for aircraft design that required the wing to be stowed when not in use. Inflatable wings are conceptually possible for any wing span and have been developed with a wing span as small as 15 cm (6in) for missile fins and as large as 9.14m (30ft) or more for LTA vehicles. The ability of the inflatable wing to be stowed has many incentives. Inflatable wing structures have the benefit of an extremely low packing volume without affecting it structural integrity. The packing volume can be more than ten times smaller than their deployed volume. Inflatable wing can be folded and stowed inside the fuselage and inflated to its designated pressure when needed.

Oklahoma State University and Dr. Jamey Jacob[5] have years of experience when it comes to inflatable structures and inflatable wings. While analyzing an inflatable airbeam, a non-rigid body, may seem like a daunting task, the equations involved at their basic level are fairly straight forward. Using simple pressure vessel equations, the necessary equation for structural analysis is derived. The equation comes from pressure vessel theory. When an inflatable beam experiences a large enough moment, the beam buckles causing the hoop stress at that point to go to zero.

Several reports were utilized in order to evaluate the airfoil of the inflatable wing. Most of the reports utilized CFD in order to evaluate different inflatable airfoils, with different numbers of baffles ranging in size and shape. From these reports, several trends were found when comparing the inflatable version of an airfoil, to their original smooth counter-part. It can be seen that the coefficient of drag and the coefficient of lift changes when the inflatable airfoil is compared to its smooth version.

This decrease in lift coefficient is a function of the airfoils angle of attack, and to lesser extent the coefficient of drag is as well. How much the coefficient of drag and lift is affected, is also very dependent of the Reynolds number that the aircraft is flying at. Inflatable airfoils tend to have an advantage over smoother airfoils at lower Reynolds numbers, as the “bumps” trip the airflow and delay the stall affects so that they occur at higher angles of attack [6-8].

Conversely, one major concern to the inflatable wing design is the lack of roll control actuator compared with conventional rigid wing design that has flap and ailerons. This problem can be tackled in several ways. One option is a servo actuation technique used to deform the wing shape to provide roll control, since inflatable wings are deformable by nature. In order to determine the wings capabilities, some initial information was required. Studies were conducted to determine the wings aerodynamic performance and its stored volume.

Therefore, the obvious trend shows that thicker wing material, longer wing span and larger chord length increase compacted volume, with these advantages, inflatable winged aircraft can be beneficial for military operation that has limited storage space at combat zone. Thus, how can inflatable wing design maintain its structural rigidity against bending load or any aerodynamic load during flight? The focus of the present paper is to evaluate the aerodynamic performance.

Theoretical Aerodynamic Performance

Inflatable wing inflates the entire wing with the inflation system. Since the wing does not have any structural elements to maintain the stiffness, it has to have high inflation pressure. It is very important to maintain the inflation pressure of the wing and because the air pressure keeps the wing in shape and the effect of the inflation pressure on the inflatable wing has been discussed elsewhere [9]. The wing also has to maintain its pressure at high altitudes and until the total mission is completed.

The surface of the resultant inflated structure has a bumpy appearance, as inflatable structures approximate the shape of a cylinder upon inflation. An example of inflatable wing cross section demonstrates that the wing appears to be a series of intersecting cylinders beam with the fabric spar position in between the intersections of the cylinders. R is the radius of curvature of the tube. The inflatable beam assumed to be a straight section. In an air structure there is a property called hoop stress. The classic equation for hoop stress created by an internal pressure on a thin wall cylindrical pressure vessel is

$$\sigma = \frac{Pr}{2t} \tag{1}$$

Where t is the wall thickness, P is the internal pressure and r is the radius. The wall is significantly thinner than the other dimensions, which implies that the difference between inner and outer radius is small. This equation shows that the bigger the diameter of the tube the greater the stress on the fabric for any given pressure. Therefore a small diameter tube can withstand greater pressure inside and still have the same amount of stress on the fabric. Now think about a long inflated tube. If the base fabric stretches, it will take more pressure inside of the tube to keep it ridged, because the fabric can stretch along the outside of the bend in the tube. This is why some inflatable structures never seem to attain the same rigidity as others.

The hoop stress can be related to the bending moment using

$$\sigma = \frac{Pr}{2t} = \frac{M_0 r}{\pi r^3 t} \tag{2}$$

Where M0, is the root bending moment. The fabric thickness does not play a major role since both sides of the equations are multiplied by the fabric thickness. Rewriting equation (2) yields:

$$P = \frac{2M_0}{\pi r^3} \tag{3}$$

Thus, larger diameter tubes are extremely beneficial when used on inflatable wings to support bending load. These explain the benefit of having a larger diameter cylindrical spar at the quarter chord to support the wing load at operating condition. Since the baffled wing consists of a series of hollowed tubes with varying radii of curvature running from the leading edge to the trailing edge, each tube acts as like an individual spar that provides additional resistance to wing bending loads.

Assumption was made that wrinkling will occur when the compressive stress due to bending becomes as large as the tensile stress due to internal overpressure. The wrinkling load is always obtained when the resultant stress cancels on the upper or the lower generative of the tube. In this location, the total stress in the tube will become zero. It is assumed that the fabric cannot sustain compressive stress and therefore, wrinkling will occur. Wrinkling can be expected at the attachment point or at location closest to the root of the wing. Collapse load is defined when the whole resultant stress cancels on one of these generative.

The primary consideration for failure in an inflatable structure is the maximum sustainable bending moment or collapse load. To determine the load carrying capability of a simplified inflatable beam design, we begin with the Euler Bernoulli beam equation that relates the beam deflection with applied moment and applied moment and material properties on a cantilever beam [26].

$$\frac{d^2 y}{dx^2} = \frac{M(x)}{E_w I} \tag{4}$$

Ew is the Young's modulus of the material, M is the applied moment, and I is the cross-sectional moment of inertia. According to Simpson et. al [10], the ILC Dover baffle design maximizes the area moment of inertia of the cross section; thus minimizing the inflation pressure required to reduce deflection and prevent buckling. Equation (4) clearly shows the relations. Main et. al modified this with respect to an inflated fabric tube to develop a relation for the bending moment equation for a single inflated fabric spar for space based inflated structures [11-12].

$$\frac{d^2 y}{dx^2} = \frac{M}{E_l \pi r^3} \quad \text{for} \quad M < \frac{\pi P r^3}{2}(1 - 2v_t) \tag{5}$$

$$\frac{d^2 y}{dx^2} = \frac{M - 2v_t \Pr^3 \sin\theta_0}{E_l r^3 \left[(\pi - \theta_0) + \sin\theta_0 \cos\theta_0\right]} \quad \text{for} \quad M > \frac{\pi P r^3}{2}(1 - 2v_t) \tag{6}$$

Where M is the bending moment. El is the longitudinal fabric tensile modulus, r is the beam radius, and θ0 is the wrinkle angle. The relation includes the impact of wrinkling and accounts for the biaxial stress in the beam fabric and the impact that it has on the wrinkling threshold of the beam as well as the beam's post wrinkling bending behavior. The model was well validated against experimental data of fabric beams under loads. As the load increases, the beam deflects in a linear manner. Once the wrinkling threshold is reached, the relation becomes non-linear. Soon after, the beam buckles. This will scale depending upon the type of structure involved. While buckling is the failure mode, the onset of wrinkling indicates the maximum design load and will be used for the design limit. It should be noted that unlike metal or composite rigid structures that will either plastically deform or crack, respectively, once the yield stress is reached, the inflatable beam will bend, but then will return undamaged to its original state after the load is reduced or removed.

Aircraft Experiments

Due to the peculiar wing airfoil, Simpson et. al [10] has investigated the aerodynamic performance of an inflatable design for MARS aircraft. Wind tunnel tests combined with smoke visualization methods were conducted on rigid model of the "bumpy" profile of the inflatable-rigidizable design with that of the ideal "smooth" profile. The initial consideration was to improve the aerodynamic performance by placing a skin over the wing to reduce the perturbation of the baffles and to provide a sharper trailing edge. At low Re case, the surface perturbation improved the flow over the wing surface. The ideal E398 airfoil performed poorly compared with inflatable profile. At AOA of 0 and Re = 25 x 103, flow separation occurs very close to the leading edge for the ideal wing and there is no reattachment. For the same conditions, the bumpy profile shows attached flow and the streamlines adjacent to the surface are not distinctly clear. This is due to the bumps tripping the flow to promote transition to turbulence earlier. It can be observed that the position of the separation region is shifted further downstream of the laminar separation point, due to the additional bumps.

In some cases, people have used these generalizations and simply estimated the CL and Cd data by modifying the data obtained from programs like XFoil, that utilizes panel theory to analyze an airfoil and produce CL and Cd information of a smooth airfoil. In other cases, they have utilized Xfoil, and modified an airfoil to have a trip placed towards the leading edge or the trailing edge to simulate an inflatable airfoil [8]. It is important to note, that one cannot simply put a "bumpy" airfoil into Xfoil or Profili and have it analyzed in order to produce this data. This is because both programs utilizes a iterative panel theory analysis technique for each panel, and the iterations are incapable of converging due to the large changes in CL and Cd.

In order to produce this vital information, the other people started to attempt to simulate the inflatable wing using Profili, by making smoother versions of the same "bumpy" airfoils in hopes that the program would be able to converge. Results were obtained, though the research people did not consider them trust worthy, and instead used them more as general guide lines that should prove similar to the actual airfoil data.

In the this paper, the Dynamic Study of an Inflatable airfoil NACA 4309, data is given for how their CL and Cd data change as a function of angle of attack, when compared to their ideal airfoil counterparts, in addition to the raw data obtained from their CFD analysis. This change in CL and Cd information was then applied to the data obtained using Xfoil for the ideal smooth airfoil by use of a percent change calculation from the data from the two sets. From this data analysis, the following CL and Cd information was obtained, shown in Fig. 1 and Fig. 2 The coefficient of drag approximately doubles, while the coefficient of lift decreases slightly. During the early design phase of this aircraft, it was estimated that the cruising speed number of approximately 30m/s. How much the lift to drag ratio is affected, shown in Fig. 3 it can be seen that the lift to drag ratio approximately increase with the angle of attack increase, and reached to the peak(20.1) at the α of 3o. The data used for the coefficient of moment was not altered in any way between the ideal and inflatable airfoil, as no information was available in the various reports, on how this coefficient is affected in inflatable airfoils.

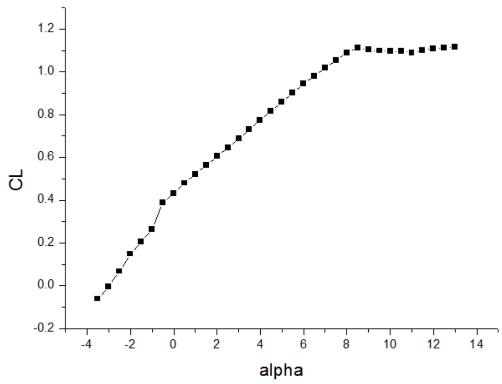

Figure 1. CL vs α; NACA 4309, V=30m/s

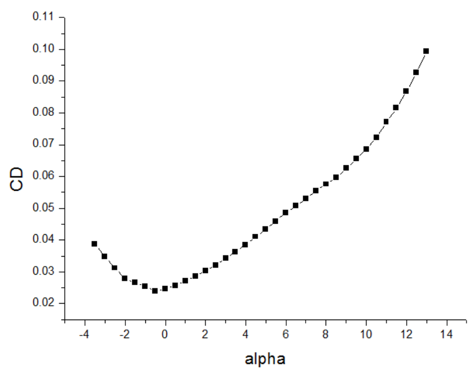

Figure 2. CD vs α; NACA 4309, V=30m/s

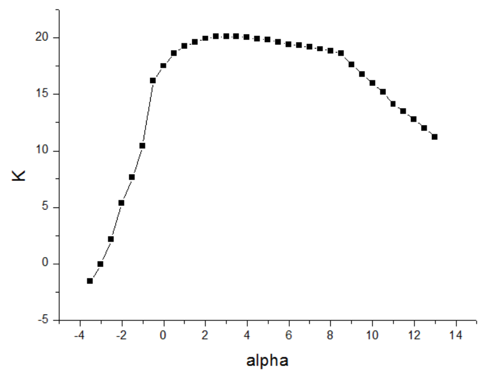

Figure 3. CL/ CD vs α; NACA 4309, V=30m/s

Summary

This paper explores aerodynamic analysis of an inflatable wing, the inflatable wing aircraft experiments were made to evaluate aerodynamic performance. First, a general NACA 4309 wing based on data analysis is derived from simulation analysis. The following CL and Cd information was obtained. The coefficient of drag approximately doubles, while the coefficient of lift decreases slightly. Next, it can be seen that the lift to drag ratio approximately increase with the angle of attack increase, and reached to the peak (20.1) at the α of 3o.

Acknowledgements

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