Evaluation of Novel Wing Design for UAV

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Abstract: Viable design alternative for the existing and fast growing UAVs, which are optimized for unmanned flight, is of great demand. Designing of a small scale UAV alternative to the AAI Aerosonde UAV Figure 1 has been considered changing the wing tail configuration of the vehicle analyzing both structural and aerodynamic performance improvements using COMSOL Multiphysics. Various Non-Planar design alternatives have been considered and box wing configuration has been proven to be the best suited for the application. Variations in the design with box wing configuration Figure 2 have been analyzed by using Tornado scrip in Matlab and the important configurations have been analyzed Figure 3 using the CFD module for aerodynamics and Multiphysics for structural performance. The NACA 0012, Ahmed body models have been very much helpful in learning COMSOL and applying it to the present situation for reducing the solving time and increasing the accuracy of solving the problem

Keywords: unmanned aerial vehicle (UAV), aerodynamics, FEM, Solid Mechanics, Wing design, Computational Fluid Dynamics

1. Introduction

During the evaluation of novel wing design concentrating on non-planar wings to replace the conventional monoplane design of the wing structure, COMSOL was used extensively to analyze structural and aerodynamic efficiencies. Over the course of the evaluation, various non-planar wings were considered starting with joined wing design where the tail reaches the wings and a tradeoff has been made keeping the same lifting surface area and reducing the size of the aircraft. Later box wing aircrafts have been considered as an alternative for the UAV. Various configurations have been tested in Tornado[1], A MATLAB script which uses vortex lattice methods in its evaluation and the particular configuration 0.5C Stagger and 1C Gap has been chosen to be the suitable box wing design. This has been proven to be aerodynamically more efficient than a mono wing and joined wing design.

1.1 Non-Planar Wing design

Non Planar wings has an advantage of reducing the induced drag without compromising with high aspect ratio keeping the aircraft small in size, suitable for a reconnaissance UAV like in the AAI Aerosonde. It has been attempted to replace the mono wing design with non-planar wings Dayton, Kroo, etc. This involves multi layered wings or a single wing which is not in a single plane. This includes ring wings, joined wings, biplanes etc. Non-planar wings are generally used for reducing the induced drag. According to Kroo[2], [3], the vortex drag of a commercial airplane constitutes to as much as 40% of the entire drag during cruise and as much as 80% - 90% of the total drag during low speed conditions like climb and take off.

1.2 Joined Wing design

Joined wing aircraft gives the advantage of a triangular configuration that ensures lightweight and inexpensive yet rugged and strong aircraft [4]. This has been invented in 1972 and there have been a lot of improvements and differences in application since then. Several conceptual designs have been made of business jets [5] and have been compared to similar

Monoplane configurations leading to several advantages such as, a 5.07% lighter aircraft that generates 1.3 times the lift and 3.5% lower drag than a similar aircraft. Apart from all these advantages, this configuration also poses some disadvantages that effect the aircraft's performance such as, as span efficiency of only 1.05 when compared to the span efficiency of a box wing of 1.46 which amounts for 28% reduction in the span efficiency when compared to the box wing configuration[2].

1.3 Box Wing design

A Box wing configuration assures saving in fuel consumption because of lower induced drag.

This reduction in induced drag is a result of higher glide ratio when compared to conventional monoplane design. In a study [6], the box wing configuration has proven to consume 9% less fuel as a result of 14% increase in the glide ratio. Also, because of the improved lift-to-drag ratio, we can expect lesser noise by the UAV making the surveillance mission without making noise [7].

Due to the above reasons, we continue the research of this thesis by creating a design alternative to AAI Aerosonde using a box wing airplane configuration.

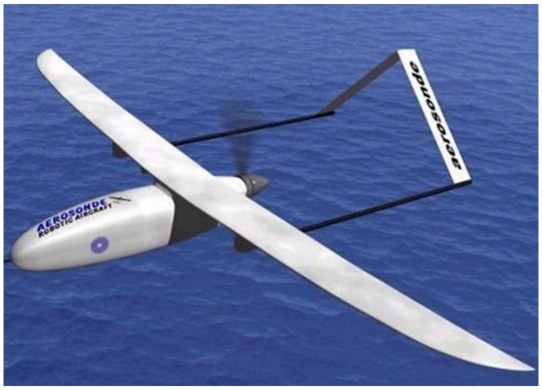

Figure 1: AAI Aerosonde aircraft

The aircraft models of all three configurations have been modelled in SolidEdge and have been imported into COMSOL using the preferred ‘parasolid’ format and using “Turbulence flow Spalart-Allmaras” Module for the Aerodynamic analysis. For the structural part, “Structural Mechanics” module has been used and found out that the best suitable aircraft configuration was determined. The aerodynamic comparison of the three aircraft configurations has been done at both 0 AOA (Angle of Attack) and 5 AOA.

2. Structural Analysis

In order to perform the structural analysis of all the models, we first take the baseline geometry AAI Aerosonde and its properties to find out both maneuver loads and gust loads and we find out the maximum loads that the Aerosonde would be experiencing through out its mission profile and apply those loads onto all three configurations and check how each wing configuration would react to those loads. To begin with, for calculating the maneuver loads, we assume a factor of safety of 1.5, which is typical for an aircraft of its mission profile and a maximum bank angle maneuver of 70 degrees. At a service ceiling of 15000ft, we calculate the ultimate positive and negative load factors, which are 2.4 and -1.8 respectively. We then calculate the equation for load factors and draw the v-n diagram for the loads

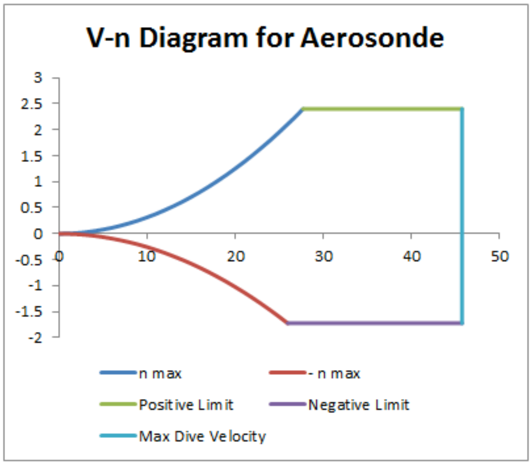

Figure 2: V-n Diagram for Aerosonde

For the Gust v-n diagram, we use the equation

$$n = 1 + \frac{K_g . V_{gE} . V_E . a . \rho}{2(W/S)}$$

Two flight conditions are considered for calculating the various load factors and we take the maximum load factor to apply the maximum loads to all three configurations. Firstly, we take the condition at sea level and calculate the load factor for both cruise condition and the diving condition, (both positive and negative). We do the same for the flight conditions for 15,000ft altitude and calculate their respective load factors. For the gust loads, we would be having 4 positive and 4 negative load factors. The highest numerical value of the load factor comes out to be 3.4199, which is higher than the maximum maneuver load factor of 2.4. Therefore, we calculate the total load using the weight from the wing loading and the span area given in [8] which comes out to be 837N. This load is distributed on the entire aircraft of Aerosonde. But for our consideration, we model in

COMSOL, only half of the aircraft taking advantage of the symmetry. That implies that we need to apply only 418.5N on the half aircraft that we are considering in COMSOL.

2.1 Evaluation in COMSOL

In COMSOL, we once the model has been imported, the entire aircraft has been given the same material (Aluminum), same load distribution (body force) and has been constrained in the same place (Fuselage). We then calculated the maximum stress and the maximum displacement after applying the same load (418.5N) to all three configurations, which would result in the following table

	Max. Stress	Max. Displacement
Aerosonde	3.38821 MPa	1.030e-3
Fixed wing	3.2897 MPa	4.455e-4
Box wing	0.50346 MPa	9.425e-6

The following equation was used to calculate the stresses on the aircraft configurations

$$-\nabla.\sigma = F_V$$

For each study, we were using the expression for calculating the von mises stresses experienced by each wing configuration

ppr(study.mises)

We then make use of the derived values to find out the maximum displacement and Maximum von mises stress for the same load.

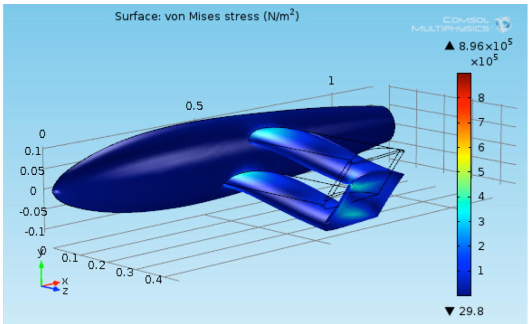

Figure 3: Von mises stress on box wing

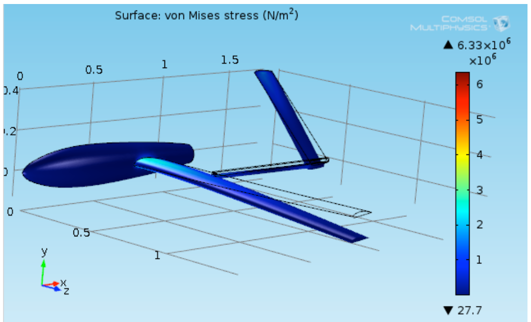

Figure 4: Von mises stress on Aerosonde

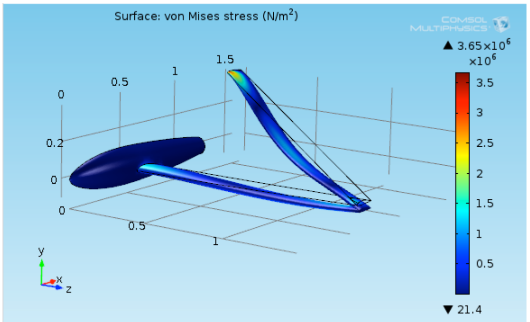

Figure 5: Von mises stress on Joined wing

3. Aerodynamic Analysis

3.1 Joined wing aircraft

Aerodynamic evaluation of the three configurations depends on the method of comparison of the aircrafts. Ideally, we need to take the same lifting surface area, typically the same plan form area in the three aircrafts. But the joined with aircraft would loose its wing shape when we apply this concept. Hence, using the MATLAB script Tornado, the baseline geometry Aerosonde and the joined wing design, the later has been downsized to match the values with that of the Aerosonde aircraft. In order to do that, the size has been decreased slowly, analyzed in Tornado and the CL for each configuration has been tabled. Below is the table with all the CL values for each configuration. The dimensions of the wing alone were changed keeping the tail position constant.

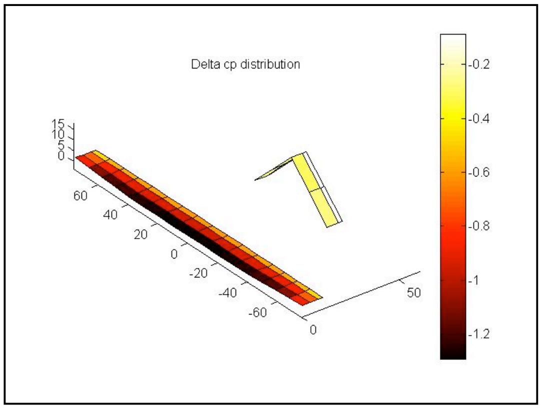

Figure 6: Aerosonde in Tornado

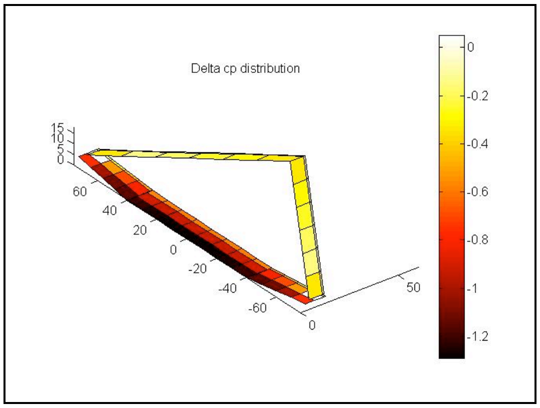

Figure 7: Joined wing in Tornado

With the above comparison, we find that there has been a reduction of 4% in the drag due to its size reduction, and also the aircraft maneuverability has been increased due to the same reason.

3.2 Box wing aircraft

For evaluating the box wing configuration, the method of comparison incorporates the Munk's theorem, in which the stagger theorem states that the total induced drag of a system of lifting elements is not changed when the elements are moved in the stream wise direction [9]. The second theorem states that when all the lifting elements have thus been translated to a single plane, the induced drag will be a minimum when the component of the induced velocity normal to the lifting element at each point is proportional to the cosine of the angle of inclination of the lifting element at that point.

Many experiments have been conducted in order to compare unconventional non planar wing configurations [3], [9]–[13] and in all experiments conducted, it is agreed that there has to be a similarity in the new configuration and equivalent monoplane configuration in order to justify the comparison. During our comparison also, we keep the following constant in order to maintain similar conditions and find out the effect of the particular areas that we are changing

- Same Center Body (Fuselage)
- Same wing Plan form Area
- Same Total Load
- Same Structural Material
- Same thickness
- Same airfoils
- Same load distribution
- Same Flying Conditions

Before analyzing the box wing configuration in COMSOL, various designs have been tested in tornado with the wing alone and the best-suited design has been incorporated with fuselage and analyzed further. Gap and Stagger has been varied and the following graph has been obtained with the results.

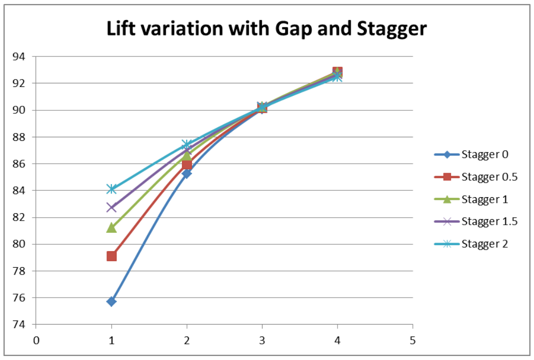

Figure 8: Lift variation with Gap and Stagger

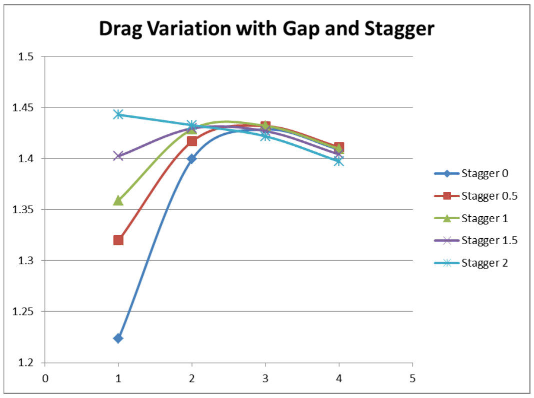

Figure 9 Drag variation with Gap and stagger

The models have been created in SolidEdge with two flight conditions (at 0 and 5 AOA) and their Total Lift and drag values have been calculated by the integration function in the derived values of COMSOL

$$n*py$$
$$n*px$$

By comparing the two aircraft configurations, we have seen a decrease of around 20% in the drag for an equivalent monoplane.

4. Conclusions

COMSOL Multiphysics 4.4 has been very helpful in the evaluation of the wing configurations giving accurate results and demonstrating the capabilities of the software. The CFD module of the software made the analysis procedure much easier than it usually would have been.

With the results obtained from the structural and aerodynamic evaluations, we conclude the using a box wing with a positive 0.5C stagger and 1C Gap between the two wing, where C is the length of the chord is best suited for the purpose. A higher Gap would result in changing the shape of the fuselage, which would violate the equivalence of the monoplane. Further analysis needs to be done before confirming the viability of the alternative design by considering the manufacturing cost, and re analyzing the models with greater details of structural materials and aerodynamic conditions reducing the number of assumptions made.

5. References

[1] T. Melin, “A vortex lattice MATLAB implementation for linear aerodynamic wing applications,” *Master’s Thesis, Dep. Aeronaut. R.* …, no. December, 2000.

[2] I. Kroo, “NONPLANAR WING CONCEPTS FOR INCREASED AIRCRAFT EFFICIENCY,” … *Adv. concepts Futur. Civ. Aircr.*, pp. 1–29, 2005.

[3] I. KROO, S. SMITH, and J. GALLMAN, “Aerodynamic and structural studies of joined-wing aircraft,” *J. Aircr.*, vol. 28, no. 1, pp. 74–81, Jan. 1991.

[4] J. Wolkovitch, “Joined wing aircraft,” *US Pat. 4,365,773*, 1982.

[5] E. F. Kim and H. Djojodihardjo, “Conceptual design and aerodynamic study of joined-wing business jet aircraft.” 08-Jul-2012.

[6] D. Schiktanz and D. Scholz, “BOX WING FUNDAMENTALS – AN AIRCRAFT DESIGN PERSPECTIVE,” *DGLR Dtsch. Luft-und* …, pp. 601–615, 2011.

[7] R. Lange, J. Cahill, and E. Bradley, “Feasibility study of the transonic biplane concept for transport aircraft application,” no. June, 1974.

[8] T. A. Mark, “Aerosonde mark 4.7: redefining expeditionary ®.”

[9] M. Andrejasic and G. Veble, “Shape Optimization of Nonplanar Lifting Surfaces and Planar--Nonplanar Break Points.,” *J. Aircr.*, vol. 50, no. 3, pp. 798–806, May 2013.

[10] B. S.Lazos, “Biologically Inspired Fixed-Wing Configuration Studies,” May 2012.

[11] B. Lazos and K. Visser, “Aerodynamic comparison of Hyper-Elliptic cambered span (HECS) Wings with conventional configurations,” *Proc. 24th AIAA Appl. Aerodyn. …*, pp. 1–18, 2006.

[12] G. Landolfo, “Aerodynamic and Structural Design of a Small Nonplanar Wing UAV,” no. January, pp. 1–12, 2008.

[13] Z. Jiaqiang, H. Junhua, X. Qifeng, F. Jinfu, and X. Hu, “Research on Aerodynamic and Hydrodynamic Performance of Conformal Semi-Ring Wing Configuration,” *Procedia Eng.*, vol. 29, pp. 3100–3104, Jan. 2012.

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