Aerodynamic design and structural optimization of a wing for an Unmanned Aerial Vehicle (UAV)

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Abstract. This paper summarizes the process of structural design, analyses and optimization for weight reduction of a UAV wing. A semi-monocoque wing structure that consists of ribs, spars and skin are efficiently optimized for weight minimization without reducing the strength to weight ratio. Initially a solid wing surface is designed with the air foil co-ordinates of NACA 2412. The CFD Analysis is carried out to get pressure distribution on various arrangements of wing by changing angles of attack. From the CFD results the variation of coefficient of lift for different angle of attack is determined. The pressure fields obtained from CFD analysis is imposed on structural members for structural analysis. Optimization of this wing is done considering various cases until the required performance is obtained. The results are obtained for the optimized wing and this helps in obtaining reduced weight of the wing and increased strength to weight ratio. Results show that substantial improvement has been achieved in comparison to the standard model.

1. Introduction
Fixed wing Unmanned Aerial Vehicles (UAV) are aircrafts that operate without a human pilot onboard. They are controlled either remotely by a human operator or autonomously through onboard computers. These UAVs shown in the figure 1, fly by making use of the lift that is generated during the aircraft’s forward motion and by the aerodynamic shape of the wing. They can be self-propelled, pure gliders or the mixture of two. Self-propelled fixed wing UAVs typically rely on forward thrust that is generated by an IC engine or electric motor powered propeller. Due to the heavier payload capabilities and long sustained flight with a minimum power makes them well suited to cover extended distances for missions such as mapping, surveillance and defense. They may also be better equipped to survive technical failure in the air, as many designs incorporate natural gliding capabilities when loss of propulsion occurs. Fixed wing UAV with a simpler structure and efficient aerodynamic design that provide the advantage of long range and endurance with high speeds. Only the wings structure of the UAV determines its efficiency in the sustained flight. The semi-monocoque wing consists of Spars, Ribs and Skin. The spar is the main load carrying member of the wing run through the tip to tip of a wing and ribs are gives the aerofoil shape to the wing placed in a frequent interval from the root to tip of the wing. The skin is very thin in nature and covers the internal structures also carry the shear loads.
For increasing the payload capacity and optimum usage of construction materials structural optimization plays an important role [1-3]. The selection of suitable aerofoil for the high altitude and long endurance (HALE) UAVs are crucial in the UAV design process [4, 5] and to face challenges in the manufacturing and reducing the cost of materials and process the optimization provides guidelines for the designers [6-8]. The development of composite also provides the effective way for reducing the weight, increased structural efficiency, and provides reduction in cost of manufacturing and maintenance [9, 10]. From the Drag polar curves, at Mach number 0.7, confirm that the plan form of a wing strongly influences the pressure distribution and the drag coefficient with a lift coefficient ranging through – 0.25 and 0.25 the curved plan form wing develops the minimum of the drag coefficient thanks to reduction of both pressure drag and shock wave effects [11,12].

2. Problem statement

Unmanned Aerial Vehicle is considered as one of the promising research fields owing to its ability in carrying out critical operations. This development will abruptly increase in the next few decades. Lift is generated by the use of wing in a fixed wing UAV. The surface area is directly proportional to the lift generated by the wing. The weight of the entire UAV increases when long span wing is used. Assuming the total weight of UAV as 6 kg and 40% of the weight as structural weight, i.e 2.4 kg is the structural weight of the aircraft. Assuming 50% of the structural weight for wing and the other 50% as fuselage, i.e 1.2 kg is the structural weight of the wings. With a help of structural optimization techniques how much weight can be reduced without reducing the strength with increase the payload capacity with long range and endurance.

3. Results and discussion

3.1. CADD modelling

The model is created by importing the co-ordinates of NACA 2412 in CATIA V5 software as indicated in the figure 2, figure 3 and figure 4. The type of wing model developed is tapered swept wing. The surface is extruded in the workbench by connecting the imported co-ordinates. The surface modelling is carried out for creating the surface. The rib at the root is modelled with 15 mm thickness and the rest of the ribs are of thickness 5 mm. The spar is welded with rib which runs from the leading to the trailing edge of the rib. There are 7 ribs that are positioned at appropriate spacing as listed in the table 1. The spar runs to the span of 1200 mm as the total length of the wing is 1200 mm. The chord length at root is 200 mm and tip is 50 mm. The wing length from root to mid measures about 400 mm and the length from mid to tip is about 800 mm. The sweep angle of the wing in the mid-section is taken as 12.4°.
3.2. CFD analysis

The imported CADD model is subjected to mesh in the ANSYS (ICEM) software and analysis in the ANSYS (fluent) software. This analysis is carried out for different angles of attack and corresponding pressure distributions are taken out. The CADD model is imported into the ANSYS (ICEM 16.0). The wing surface alone is imported without the internal parts. After importing, the wing is sectioned and named as leading edge, trailing edge, wing tip and root to obtain fine meshing. A hemispherical control volume is created and the symmetry is created along the root of the wing in the geometry. The medium inside the far field is considered as air. Once the geometry is created, the model is now subjected to meshing.

3.3. Meshing

Tetrahedral meshing is done on the wing along with its control volume and symmetry. The obtained Mesh is now checked for its quality, skewness and orthogonality. Total number of elements after
meshing is 19,05,495 and the total number of nodes is 3,24,509. Prism layers are now created on the mesh to capture boundary layer with less numerical diffusion. The model is again checked for its quality, skewness and orthogonality. Total number of elements after the formation of prism layers is 25,78,240. The mesh used in the analysis is shown in the figure 5.

![Mesh on wing](image)

**Figure 5.** Mesh on wing.

3.4. *Solver input and boundary conditions*

The problem consists of flow around the airfoil at various angles of attack (-3, 0, 3, 6, 9, 12, 15, 18). The inputs and boundary conditions are presented in the table 2 below.

| Input               | Value                        |
|---------------------|------------------------------|
| solver              | Pressure based               |
| State               | Steady state                 |
| Viscous model       | Transition-k epsilon         |
| Material            | Air                          |
| Density             | 1.17664 kg/m³                |
| Mach number         | 0.2                          |
| Temperature         | 300 K                        |
| Enthalpy            | 4271.293 J/Kg                |
| Pressure            | 101325 N/m²                  |
| Reynolds number     | 6.38×10⁶                     |

**Table 2.** Inputs given in CFD analysis.

3.5. *CFD analysis and results*

The mesh file from ANSYS is imported into the software FLUENT 16.0. The analysis at zero angle of attack is done applying appropriate boundary conditions. The pressure values are obtained and the values of lift and drag are calculated. The same procedure is repeated for other angles of attack and the corresponding values of lift and drag are calculated. The static pressure values obtained from the analysis for each angle of attack is exported as a NASTRAN file. The contours of pressure obtained for various angles of attack from CFD simulations are shown in the figure 6 and figure 7. According to the Bernoulli’s principle the top surface will experience lower pressure when compared to the bottom surface. Hence, the wing is effectively pushed upward normal to the incoming flow stream.
Figure 6. CL vs angle of attack.

Figure 7. Pressure contours at alpha 18°.

3.6. Structural analysis

The CADD model from CATIA is imported into MSC PATRAN. It is then subjected to meshing and the analysis is done from the results obtained from CFD. The CADD model of the wing along with the ribs and spars, which is saved as a STEP file is imported into a new database in the MSC PATRAN software. Total mass of the model is 2.27kg.

3.7. Structural meshing

The type of mesh created on the model is two-dimensional shell mesh. Initially, the ribs are meshed with quad and tri elements. Then, the spars are meshed using quad elements with respect to the mesh of the ribs to maintain the connectivity. Eventually, the skin is also meshed with quad elements maintaining the connectivity. Once the mesh is completed as shown in figure 8, equivalence is done and the FE model is verified.

Figure 8. Mesh on skin.

The pressure load at zero angle of attack is applied on the cantilever wing surface and analyzed for the structural stress and deformations are indicated in figure 9 and figure 10.
4. Optimization

In order to increase the performance and reduce the weight of the wing, optimization is carried out. Series of optimization for angle of attack 0° is done to obtain better results. Here, manual optimization is carried out.

4.1. Optimization-1

Standard model after the analysis is taken into account. For optimization, the thickness of the skin is reduced to 1mm and analysis is carried out. The results are mentioned in the table 3 and result contours are displayed in the figure 11.

4.2. Optimization-2

Mass of the ribs is reduced by creating cut-outs and analysis is carried out for angle of attack 0°. Optimized structure and resulting stress distributions are shown in the figure 12 and figure 13 below.
4.3. **Optimization-3**

Further optimization is done by reducing the number of ribs from 7 to 5. Analysis is carried out and results are obtained. The optimized structure is shown in the figure 14.

![Figure 14. Von-mises stress on surface and spars and ribs (opt-3) in MPa.](image)

4.4. **Material Optimization-1**

To reduce the weight of the wing further optimization is done. Now the material of the wing is changed from aluminium to composites. Composites are anisotropic material whose properties are directional dependent. For the case of laminate composite, each lamina is a continuum and behaves as a linear elastic material. Composites are used more in the aerospace industry due to its less weight and high strength. The composite material that we chose for the optimization process is Carbon epoxy, which is extremely strong and light according to the symmetric laminate is created in such a way that it has 8 layers of lamina in an orientation of [0/90/45/-45] with a thickness of about 0.15mm. After the change in material of the wing structure, analysis is carried out. The material properties of the composite are listed in the table 3. The corresponding contour results are shown in figure 15.

![Table 3. Properties of carbon-epoxy.](image)

| Property            | Value                  |
|---------------------|------------------------|
| Young’s modulus     | $E_{11}$ 70GPa         |
|                     | $E_{22}$ 25GPa         |
| Poisson’s ratio     | $\nu$ 0.1              |
| Shear modulus       | $G_{12}$ 5 GPa         |
| Density             | $\rho$ 1.6 gm/cm³      |
4.5. Material Optimization-2

Further optimization is done to reduce weight by applying 4 layers of carbon-epoxy lamina on the skin and 8 layers of lamina on the ribs and spars. Analysis is carried out and the results are obtained as indicated in the figure 16 and figure 17.

**Figure 15.** Layer stress obtained on surface and stress on spars and ribs (opt-4) in MPa.

**Figure 16.** Layer stress obtained on surface and Von-mises stress on spars and ribs (opt-5) in MPa.

**Figure 17.** Deformation of the wing (opt-5) in mm.
Table 4. Optimization results.

| Properties          | Structural optimization -1 | Structural optimization -1 | Structural optimization -1 | Materials optimization -1 | Materials optimization -2 |
|---------------------|-----------------------------|-----------------------------|-----------------------------|----------------------------|----------------------------|
| Mass (Kg)           | 1.46 (36% reduced from standard model) | 1.42 (38% reduced from standard model) | 1.35 (41% reduced from standard model) | 0.64 (72% reduced from standard model) | 0.35 (85% reduced from standard model) |
| Stress (MPa)        | 16                          | 16.3                        | 18.1                        | 21.7                        | 49.3                        |
| Deformation (mm)    | 10                          | 10                          | 10.9                        | 17.5                        | 32                          |

5. Conclusion

From the above optimization process results indicated in the table 4 above, 40% of the mass is reduced in the optimized wing and the strength to weight ratio of the standard model is 7.47 whereas the optimized wing has strength to weight ratio of 31.8. The optimized wing is found to have more strength to weight ratio in comparison with the standard model. The factor of safety is an important parameter in the design of aerospace structures. From the above analysis we found that, for the optimized structure of the wing with the assumed dimensions the structure is safe even if the loads are six times more than the load that is applied, considering the factor of safety as 6.

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