Structural analysis and topology design optimization of load bearing elements of aircraft fuselage structure

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Abstract. Aircraft total weight plays a major role in aircraft design which results in additional payloads and better performance. There are many ways to reduce weight of aircraft structures, for example, using composite materials. Composite materials such as CFRP offer significant weight reduction for aircraft. Weight reduction improves fuel efficiency of the aircraft which results cost of savings. Besides using these light materials structural design optimization is currently a valid methodology which is applied in advanced engineering. Topology optimization is used to yield an optimized shape and material distribution for a set of loads and constraints within a given design space. Whereas this paper deals with topology optimization of fuselage ribs. By using this optimization technique, weight can be reduced 18.36 % of the original weight.

1. Introduction
Composite materials are widely used in the aerospace industry due to its characteristics and are replacing with the traditional engineering materials. So aircraft manufacturers have been gradually increasing its reliance on composite materials. Carbon fiber-reinforced plastic (CFRP) is apparently an ideal material for an aerospace structures: its strength is comparable to that of steel and its density is half of average aluminum alloy used for aircraft manufacturing.

Optimization is a process of selecting a final solution amongst a number of possible options, such that a certain requirement or a set of requirements is best satisfied i.e. a design in which some quantifiable property is minimized or maximized (e.g., strength, weight). Optimization techniques play an important role in structural design, the very purpose of which is to find the best ways so that a designer or decision maker can derive a maximum benefit from the available resources. In our work, we are studied the optimization through topology methodology [1].

Topology optimization is a mathematical method that optimizes material layout within a given design space, for a given set of loads, boundary conditions and constraints with the goal of maximizing the performance of the system. The conventional topology optimization formulation uses a finite element method (FEM) to evaluate the design performance [5].

Ansys topology optimization [9] can be used to find the maximum stiffness, the minimum volume and maximum natural frequency of the structure. The objective function of the topology optimization reduces the structural strain energy on the condition of meeting the structural constraints. To reduce the strain energy means to increase the stiffness of the structure.

The objective of this paper is to analyse the structural modelling calculation of load bearing elements and to achieve an optimal design by using topology optimization. In order to meet this goal,
we created 3D model of rear fuselage structure. After that, simulation calculation is performed in Ansys fluent and then carried out to structural analysis. Finally, topology optimization had been done in Ansys and obtained new design, which could reduce the mass of the whole body and compact with our objectives.

2. Objects and materials
The object of our work is rear part of fuselage structure of Diamond DA 62 aircraft (figure 1) made by CFRP. Rear fuselage consists of four ribs and fuselage skin. Performance characteristics (table 1) and physical-mechanical characteristics CFRP (table 2) are shown in following tables.

| Table 1. Performance characteristics of DA 62 [10] |
|-----------------------------------------------|
| Performance | Index (SI) |
|------------|------------|
| Maximum speed (14,000 ft.) | 352 km/hr |
| Cruise speed at 75% (12,000 ft.) | 317 km/hr |
| Maximum stall speed ($V_s$) | 191 km/hr |
| Maximum rate of climb (MSL) | 5.2 m/s |
| Empty Weight | 1590 kg |
| Maximum take-off mass | 2300 kg |

![Figure 1. Basic dimensions of DA 62](image)

| Table 2. Physical-mechanical properties of CFRP |
|-----------------------------------------------|
| Property | Unit | Value |
|----------|------|-------|
| Density | kg/m³ | 1480 |
| Young’s Modulus, $E_1$ | GPa | 91.82 |
| Young’s Modulus, $E_2$ | GPa | 91.82 |
| Young’s Modulus, $E_3$ | GPa | 9.00 |
| Shear Modulus, $G_{12}$ | GPa | 19.500 |
| Tensile strength | MPa | 829 |
| Compressive strength | MPa | 439 |
| Shear Strength | MPa | 120 |

3. Modeling and simulation calculations
To calculate the structural strength and to obtain the new design model, we used Ansys topology optimization. For this optimization we need to draw 3D model of structures and consider the acting load on the structure.
3.1. Load conditions

In accordance with Aviation Rules of Russian standards [7], the calculation of the static strength of aircraft is considered upon the external loads acting on the aircraft and its individual units in various calculation cases. In the description of those calculation conditions show the aircraft position, characteristic of flight, failure load factor and safety factor, direction and distribution of loads. Basic calculation conditions according to Aviation Rules are classified as A, A', B, C, D and D' (figure 2).

In this paper we analyzed the loads based on the calculation condition A. It may occur when exiting a planning or executing a climb conditions. In condition A, aircraft is in curvilinear flight at an angle of attack ($\alpha$), which provides the maximum lift coefficient ($Cl_{\text{max}}$) of the wing.

![Figure 2. Calculation conditions according to Aviation Rules [7]](image)

The climb performance can be simply calculated using a balance of the forces acting on the aircraft. The aircraft is assumed to be climbing at a constant angle ($\Theta$) and at constant forward velocity ($V$). The balance of forces (figure 3) can be described as the following.

$$Y = G \cdot \cos(\Theta),$$

$$P - X = G \cdot \sin(\Theta),$$

where, $Y$ – lift force (N), $G$ – weight (kg), $P$ – thrust force (N), and $X$ – drag force (N). And the climb speed of aircraft can be written as the following equation.

$$V_{\text{climb}} = \sqrt{\frac{2 \cdot G \cdot \cos(\Theta)}{Cl \cdot \rho \cdot S}},$$

![Figure 3. Equilibrium of forces in climb condition [8]](image)
where, $C_l$ – coefficient of lift force, $\rho$ – density of air at flight altitude (kg·m$^{-3}$) and $S$ – wing surface area (m$^2$). In condition A maximum load factor is taken as 2.5 and body forces become 2.5·G. However, this force appears in two components base on angle of attack: 2.5·G·cos ($\alpha$) and 2.5·G·sin ($\alpha$).

3.2. Methodology of modelling

The 3D geometry of aircraft is created using SolidWorks [6], and it is imported to Ansys fluent to determine the aerodynamic pressure acting on the aircraft fuselage (figure 4). Inflation layers are set to 5 and the total thickness is 50 mm. We used maximum face size 200 mm. The meshed model contains more than 8 million elements and about 2 million nodes.

According to flight and aerodynamic theories, acting load on aircraft in maneuver will be the maximum at sea level. So we are taking account into atmospheric conditions such as density $\rho = 1.225$ kg·m$^{-3}$, pressure $P = 101325$ Pa and viscosity of $1.71\times10^{-5}$ Pa·s$^{-1}$. Maximum pitch angle of flight trajectory $\Theta = 10^\circ$ and for condition A we used maximum velocity of maneuver: $V_x = 52,195$ m/s and $V_y = 9.20$ m/s.

![Figure 4. Pressure distribution on the aircraft body, Pa](image)

After finding aerodynamic pressure in Fluent, the structural analysis has been done for the topology optimization in ANSYS Static Structural. In this structural calculation we considered load conditions only on the rear part of aircraft. The structural analysis is done in static structural under given load condition (figure 5-6).

![Figure 5. Total deformation of Original structure, mm](image)

![Figure 6. Von-Mises of Original structure, MPa](image)
The design region is allowed to be optimized whilst the exclusion region is a fixed geometry and cannot be optimized by the solver. In this paper, the outer surfaces of ribs and fuselage skin are kept as an exclusion region as it is important to not change any aerodynamic surfaces for the performance of the fuselage. All boundary conditions automatically become exclusion regions. After topology optimization, the new design model is obtained (fig 7a). After topology optimization process we had to perform a validation step, in which we rerun our static simulation with the loads and constraints, which are mentioned above. So, this output model is modified to get smooth faces and optimized shapes (figure 7b).

![Figure 7. Comparison of rib shapes: a) topology output shape; b) modified shape](image)

After that, we transfer it to structural analysis. The resultant values of deformation and maximum von-Mises stress based on new design model are shown in following (figure 8-9).

![Figure 8. Total deformation of New structure, mm](image)

![Figure 9. Von-Mises of Original structure, MPa](image)
According to the results of validation step, the values of maximum deformation and von-Mises stress obtained by the structural strength modeling of rear part fuselage structures with new design ribs are not exceed strength limits.

4. Results and Conclusion
The objective of our work is to analyse the structural strength calculation and topology optimization of design structure. So, the reduction of mass is the main result along with the non-much change of deformation and stresses under the same load conditions.

| Parts     | Original design mass, kg | New design mass, kg | Weight reduction, % |
|-----------|--------------------------|---------------------|---------------------|
| 1st rib   | 8.1319                   | 7.8125              | 3.928               |
| 2nd rib   | 5.4519                   | 3.4577              | 36.58               |
| 3rd rib   | 3.1415                   | 2.2898              | 27.11               |
| 4th rib   | 1.9082                   | 1.6521              | 13.42               |
| Total     | 18.6331                  | 15.2121             | 18.36               |

New design model of ribs obtained by topology optimization is 18.36 % lighter as compare to the initial rib design for the same load conditions (table 3).

The present work illustrates how topology optimization in Ansys may be used in the design of aircraft components. The application of this optimization give as possible and perspective design structure of load bearing elements of light aircraft structures and allows reducing the mass of structure.

In our paper only calculation condition A is taken as load case. There are other 5 calculation conditions, which have different boundary conditions. So, as for future work, we will analyse structural strength calculations and topology optimizations base on other calculation conditions.

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