Parametric and topology optimization of load bearing elements of aircraft fuselage structure

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Abstract. This paper presents the weight reduction of load bearing elements of aircraft DA-62 fuselage structure using parametric and topology optimizations methods. The structural analysis of rear part of aircraft fuselage in various load calculation conditions is performed. In the first step using parametric optimization of structure, allow to reduce its mass to 15.84 %. In addition using topology optimization of optimized structure by parametric modeling added mass reduction to 32.87% of total structural mass.

1. Introduction
Reducing the weight of the structure is one of the priorities of the development of modern aviation technology, as it allows increasing the economic efficiency of aircraft. To achieve this goal in the design of aircraft are increasingly introduced composites, superior in many parameters, especially specific strength and stiffness, traditional metal materials. For example, the Boeing 787 fuselage is built in five main sections consisting of composite material that account for 50% of the aircraft’s total structural weight.

A perspective approach to reducing the weight of the power structure is the use of optimization methods. Optimization is a process of selecting or converging onto 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, strength-to-weight ratio). In recent years, traditional approaches based on parametric optimization have been added by topological methods [1–3]. 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 purpose of topological optimization is to determine the optimal material distribution in the design of structure under specified loads, and meet the optimization criteria, in other words, finding the optimal placement of material in design, so that the target function have a maximum or minimum value of boundary conditions. In topology optimization, the desired result in a material distribution function in the design area [4]. In this study, the ANSYS Topology Optimization [5, 6] module based on SIMP method is used.

2. Objects and materials
The object of our work is rear part of DA-62 fuselage structure that consists of fuselage skin and load bearing elements: four oval shaped ribs (figure 1). The aircraft is available in two weight versions. The European version has five seats and maximum takeoff weight of 1,999 kg, the US version has seven seats and a 2,300 kg [7]. The later version is used as a model object of our work. The general characteristics of DA 62 are shown in table 1. The fuselage skin and its load bearing elements ribs are
made of carbon fiber-reinforced plastic (CRFP) based on carbon fabric WL-Blatt 8.3520.80 that made it possible to simultaneously provide strength and light weight structure of aircraft.

### Table 1. Performance characteristics of DA 62 [7]

| Performance                        | Index (SI) |
|------------------------------------|------------|
| Maximum speed (14,000 ft.)         | 353 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    |
| Useful Load                        | 710 kg     |
| Maximum take-off mass              | 2300 kg    |

Physical-mechanical characteristics of CFRP are shown in the table 2.

### Table 2. Physical-mechanical properties of CFRP

| Parameter                  | Unit | Values |
|----------------------------|------|--------|
| 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    |

It is necessary to determine the loads acting on the rear part of fuselage structure for the design optimization process. Firstly, 3D model (figure 1) of the structure is modelled in NX software. After that simulation calculation is performed in ANSYS module Fluent to determine the aerodynamic loads acting on the aircraft in flight condition.

![3D model of rear part of fuselage structure](image.png)

**Figure 1.** 3D model of rear part of fuselage structure

### 3. Optimization of load bearing elements of fuselage structure

#### 3.1 Calculation load conditions

In accordance with Aviation Rules of Russian standards [8], 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).

Figure 2. Loads acting on the aircraft in various load cases

3.2 Finding aerodynamic loads acting on the aircraft

For the simulation calculation processes, the 3D geometry of aircraft is modelled using FEM software SolidWorks [9] and it is imported to ANSYS Fluent. For the airflow simulation process the mesh model of more than 8 million elements and about 2 million nodes was created. The mesh should also include a boundary layer to solve lamina flow equations. For the model of our analysis the amount of layers in the boundary is set to 5 and the total thickness is 50 mm. Since the aerodynamic load acting on the aircraft will be the maximum when performing maneuvers at sea level, the ambient pressure was assumed to be equal to \( p = 101325 \) Pa and the air density \( \rho = 1.225 \) kg/m\(^3\) [10–15].

As a result of the simulation, the pressure distributions on the surface of the aircraft were determined for all six calculated cases (table 3).

Table 3. Maximum total pressure acting on the aircraft in various load conditions

| Conditions | A     | B     | C     | D     | A’    | D’    |
|------------|-------|-------|-------|-------|-------|-------|
| Pressure, Pa | 103219 | 107602 | 10700 | 105625 | 107747 | 107244 |

3.3. Parametric optimization of fuselage structure

Simulation of the stress-strain analysis of the fuselage structure was carried out in the ANSYS Static Structural. It was considered that both aerodynamic and mass-inertial loads are subjected on the structure. At the same time, the change in the direction and magnitude of the load factor \( f \) was also considered in calculation process. As a result, the stresses and displacements in ribs of the rear part of fuselage structure were determined.

At the first stage of the study, the question of choosing rational values of geometric dimensions of the profile of frames was solved based on the parametric optimization method (figure 3). Firstly, three variants of the width \( b \) of ribs: 50, 100 and 150 mm were compared and the variant in which the stresses in ribs set a minimum value was chosen for further analysis. The obtained values of stresses \( \sigma, \) MPa), displacements \( \delta, \) mm) and the total mass of frames \( m, \) kg) are given in the table 4.
Figure 3. Geometric parameters of oval-shaped rib

Table 4. Structural modeling results of load-bearing elements of fuselage structure with different width

|      | I          | II   | III            |
|------|------------|------|----------------|
|      | $b - 50$ mm| $b - 100$ mm (Base model) | $b - 150$ mm |
| $m$, kg | $\delta_{\text{max}}$, mm | $\sigma_{\text{max}}$, MPa | $m$, kg | $\delta_{\text{max}}$, mm | $\sigma_{\text{max}}$, MPa | $m$, kg | $\delta_{\text{max}}$, mm | $\sigma_{\text{max}}$, MPa |
| 34.80 | 2.09       | 62.38 | 41.35 | 1.083 | 89.15 | 47.87 | 1.813 | 68.787 |

Next, the problem of optimizing the thickness ($t$) of the rib was solved, and variants with a thickness of 10 mm to 25 mm were analyzed (table 5).

Table 5. Structural modeling results of load-bearing elements of fuselage structure with different thickness

|      | I          | II   | III          | IV           |
|------|------------|------|--------------|--------------|
|      | $t - 10$ mm| $t - 15$ mm | $t - 20$ mm | $t - 25$ mm |
| $m$, kg | $\delta_{\text{max}}$, mm | $\sigma_{\text{max}}$, MPa | $m$, kg | $\delta_{\text{max}}$, mm | $\sigma_{\text{max}}$, MPa | $m$, kg | $\delta_{\text{max}}$, mm | $\sigma_{\text{max}}$, MPa |
| 20.7  | 3.455      | 79.9 | 2.77 | 27.7 | 64.5 | 34.8 | 2.09 | 62.38 | 41.9 | 1.57 | 76.6 |

The second step analysis results show that the variant with the thickness of 20 mm has the minimum stress value and it is selected for the third step. In the third step, we varied the height of ribs ($h$): 60 mm, 80 mm, 10 mm and 120 mm respectively (table 6). As a result, it was found that the rational set of geometric parameters of frames is: width ($b$) -50 mm, thickness ($t$) -20 mm and height ($h$) – 100 mm.

In total, the parametric optimization of the size of the ribs of rear part of fuselage was able to reduce its mass by 15.84%, from 41.35 kg to 34.8 kg.

Table 6. Structural modeling results of load-bearing elements of fuselage structure with different thickness

|      | I          | II   | III          | IV           |
|------|------------|------|--------------|--------------|
|      | $h - 60$ mm| $h - 80$ mm | $h - 100$ mm | $h - 120$ mm |
| $m$, kg | $\delta_{\text{max}}$, mm | $\sigma_{\text{max}}$, MPa | $m$, kg | $\delta_{\text{max}}$, mm | $\sigma_{\text{max}}$, MPa | $m$, kg | $\delta_{\text{max}}$, mm | $\sigma_{\text{max}}$, MPa |
3.4 Topology optimization in ANSYS

At the second stage, the topology optimization of the shape of the ribs was carried out, and the result of parametric optimization was used as the starting point. In this paper, the total weight of ribs of the fuselage structure is chosen as the target function, and the maximum allowable stress in the structure is set as a limit. For the topology optimization algorithm, determined the design area, the topology of which can be changed and the area for which such changes are not allowed [6]. Here, the entire volume of the ribs was used as a design area, except for the outer surfaces of the ribs, which are needed to join with the skin. As a result of topology optimization, a new variant of load bearing elements of rear part of the aircraft was obtained (figure 4).

Figure 4. Geometrical model of load bearing element of fuselage structure, obtained by using topology optimization

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 imported to Siemens NX in order to modify to get smooth faces and optimized shapes and then transfer it to structural analysis (figure 5).

Figure 5. Results of structural analysis of validation step: a) deformation, mm, b) equivalent stress, MPa
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 far different from the results of initial design model modeling results.

4. Results and Conclusion

Thus, a new version of the design of the load bearing elements of fuselage structure is proposed and its total mass is 32.87% less than the original version for the same loading conditions (table 7).

| Parts | Mass of initial design model kg | Mass of new design model, kg | Mass reducing, % |
|-------|---------------------------------|------------------------------|-----------------|
| 1st rib | 17.98                           | 11.483                       | 36.13           |
| 2nd rib | 11.75                           | 7.7039                       | 34.13           |
| 3rd rib | 6.307                           | 4.8584                       | 29.90           |
| 4th rib | 4.876                           | 3.7124                       | 20.80           |
| Total  | 41.3483                         | 27.7577                      | 32.87           |

As a result of a complex of computational and theoretical studies, a new original design of load bearing elements of DA62 aircraft was proposed, which has higher weight characteristics compared to the original version.

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