Ultralight structurally optimized carbon fibre reinforced polymer composite wing designing based on parametric modelling and topology optimization

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Abstract. The passenger aircraft wing is an extremely complex object, especially in design, in which it is necessary to take into account many different factors, physical processes and phenomena both in individual areas of science and engineering, and at their junction. The main enlarged areas and issues that are solved during the development of wings include aerodynamics, aeroelasticity, strength, stability, and manufacturability. All this causes significant time and labour costs, especially at the stage of design calculations. In this connection, the urgent task of compiling a universal integrated methodology for designing a wing of polymer composite materials, which allows to accelerate and facilitate the selection of design parameters at the stage of outline design. The methodology being developed is tested on the passenger aircraft wing and takes into account the choice of the geometric shape of the wing, taking into account optimal aerodynamics and minimizing the operating loads, determining the position of the main power elements providing the necessary structural strength, as well as calculating the main structural parameters of individual polymer composite elements.

1. Introduction
Currently, in connection with the design and manufacture of a new generation of passenger aircraft, the proportion of the use of polymer composite materials (PCM) with carbon fibre in the structure is increasing (up to 50%). In this connection, the design and justification of PCM structures and parts, with the required reinforcement scheme, plays a key role in ensuring the operability of the critical load-bearing power elements of the aircraft.

One of the most important elements of the aircraft body is a wing designed to create aerodynamic lift and ensure lateral stability. Currently, carbon fibre reinforced polymer composite wings, which allow for mass efficiency without compromising performance.

Work in the field of wing design techniques is actively carried out by both international and domestic experts, however, they are disparate in nature and are aimed at certain tasks, in particular, optimization of existing structures using various methods, studying aerodynamics and wing loads, and obtaining design structural and structural arrangement (SA).

Some studies are focused on the study of aerodynamics and wing loads [1], which are not limited only to experiments and process modelling using computer-aided design (CAD) systems, but also combine these results to obtain the most accurate data [2]. Some works [3] also include strength calculation, however, the results are limited to obtaining the design SA of the product. Much attention is paid to methods for optimizing an existing design using various methods. In particular, the use of
genetic algorithms [4, 5], Kriging models [6]. Particular attention is paid to the calculation and optimization of the weight of the wing structure [7], including the use of curved force elements [8, 9]. In addition, PCM panels [10] with integrated stringers [11, 12] are considered as an object of optimization. Work is underway to study the properties of PCM stacks other than quasi-isotropic [13, 14]. For a rational layout that takes into account multivariate analysis, methods of multidisciplinary optimization are used [15, 16], optimization of non-traditional aerodynamic layouts of an aircraft is considered [17, 18]. Separate studies are carried out not only in the field of rational arrangement of the engine to minimize power consumption and create efficient traction, reduce fuel consumption required for the flight of a subsonic aircraft, but also the effect on the aerelasticity of the aircraft [19, 20]. Much attention is paid to various physical processes, their description during the formation of ice on the surface of the apparatus and related phenomena [21], for example, the effect of ice roughness [22], modelling of airborne droplets and the processes of moisture loss on a streamlined surface [23]. Also, when designing aircraft, topological optimization is applied using volumetric modelling methods [24] using finite elements in conjunction with the basic algorithms for structural design and engineering analysis [25] to determine the layout scheme and dimensions of the future product [26].

In general, it is logical to state that the work associated with the development of a comprehensive methodology that takes into account all the stages of designing a wing and its elements from PCM, starting with primary geometry and ending with the parameters of parts, is fragmented. Design stages carried out at aviation enterprises are a trade secret. Based on the foregoing, the work is devoted to the urgent task of designing a wing made of carbon fibre reinforced polymer composite.

2. Goals and General Structure of the Methodology

The purpose of the work is to develop a design technique for a carbon fibre reinforced polymer composite wing, combining both designing of structural elements and individual power elements, using topological optimization methods, taking into account pronounced anisotropy of material properties, taking into account operational loads [27-30].

In the framework of the goal, a number of problems are solved in connection with the design of an ultralight PCM wing:

- Development of geometric models of the wing with an internal power set
- Determination of operational loads at various flight modes
- Determining the degree of influence of the calculation characteristics and the model on the results
- Optimization of geometric parameters of wing PCM elements
- Topological optimization of wing elements
- The use of structurally adapted curved layouts of the material in the wing structure

These tasks are solved in accordance with the proposed methodology, which includes a number of successive stages, and allow you to develop the primary geometry of the ultralight PCM wing:

- The choice of primary geometric shape options, i.e. aerodynamic profile, scope, area
- Carrying out calculations to obtain loads for a given flight mode (speed, angle of attack, altitude)
- Design of the SA (selection of the number and location of power elements: spars, ribs, stringers)
- Designing of individual power elements of the PCM structure (selection of material, reinforcement scheme, wall and belt thicknesses, geometric profile, etc.)

The methodology was tested on the carbon wing of a medium–range passenger aircraft.

3. Rationale for Geometric Dimensions and Calculation of Wing Aerodynamic Load

3.1. Source data

Based on the analysis of the fleet of existing medium-range aircraft, a number of wing variants with a wingspan of 35 m were simulated. For the calculation, the absolute flight altitude of 11500 m was
adopted, the atmospheric parameters were selected in accordance with standard values. We considered the cruising flight mode at a speed of 870 km/h, and the angles of attack, respectively: 0°, +11°, −7°.

The parametric calculation for determining the aerodynamic load on the wing was carried out in the ANSYS software package using the CFX module. Based on existing aircraft, 12 variants of wing geometric models were built (Figure 1). When choosing the geometric shape of the wing, the following varied: sweep angle along the leading edge (χ); the angle of the transverse V wing (ψ); plan view of the wing (with a straightened section and without a straightened section); aerodynamic profile.

3.2. Results
As a result of the calculation, the aerodynamic loads on the wing were determined: wing pressure, temperature as a result of aerodynamic heating, flow directions near the wing surface. In Figure 2, as an example, individual calculation results are presented, data on the swept wing, with a symmetrical aerodynamic profile, with a sweep angle along the leading edge χ = 29°, a transverse angle V, ψ = +6°, and an angle of attack α = 0° are presented.

Figure 1. Type of computational model of the medium flowing around the wing with boundary conditions: 1 – inlet, 2 – outlet, 3 – symmetry.

Figure 2. Pressure distribution along the wing profile [Pa 10^3].

Figure 3 shows the individual results of calculating the pressure distribution over the wing profile from the relative coordinate of the point (\( \bar{x} = x/c \)), where x is the coordinate of the point in the profile section and c is the profile chord length in this section.

Figure 3. Pressure distribution p along the wing profile for an angle of attack of 0°, kPa.
After analyzing the calculation results, the option of the swept wing with an asymmetric aerodynamic profile, with a sweep angle along the leading edge $\chi = 29^\circ$, a transverse angle $\psi = +6^\circ$, with a straightened section was selected.

4. Selection of Wing Structural–Arrangement

4.1. Source data
The calculation was carried out for three calculated cases: angles of attack $0^\circ$, $+11^\circ$, $-7^\circ$. The load values were obtained when simulating the problem of external aerodynamics and were imported into the calculation. In the side section, the wing is limited in movements and turns about the axes. The elements of the SA were modelled flat, with the assignment of the corresponding thickness in groups. 90 variants of the SA were modelled. When choosing the SA, the pitch of the spars (% of the chord), stringers, ribs (% of the average aerodynamic chord), the direction of installation of the ribs (in flight, perpendicular to the spar) were varied.

Taking into account the varied parameters, 210 calculated cases of SA are considered in the work.

4.2. Results
As a result of mathematical modelling, the stress-strain states are determined and the values of the wing displacement under the action of aerodynamic loading are obtained. The Pareto set is determined by two criteria – the minimum mass and the minimum deflection corresponding to the maximum load-bearing capacity of the structure (Figure 4). The choice of the best option was made by determining the shortest distance to the ideal centre.

After analysing the calculation results, the SA option was selected with the parameters presented in Table 1, where MAC is the Mean Aerodynamic Chord.

| Front spar pitch (% of chord) | Rear spar pitch (% of chord) | Ribs pitch (% MAC) | Ribs mounting orientation | Stringer pitch (m) |
|------------------------------|-------------------------------|--------------------|---------------------------|--------------------|
| 20                           | 70                            | 40                 | Perpendicular             | 0.2                |

5. Influence of Airliner Core Elements and Icing on Aerodynamic Load Definitions

5.1. Source data
The influence of the main elements of the aircraft on the aerodynamic loads from high-speed pressure was studied by examining a separate aerodynamic surface of the wing as part of the aircraft, a wing with an engine nacelle mounted on a pylon below it, and separately the aerodynamic surface of the wing
The influence of the size of the computational domain and the grid of finite volumes on the surface of the objects of study was considered on several options with different dimensions. When considering the dimensions of the computational domain, the variable distance from the surface of the object under study to the boundary varied from 3 to 30 chord lengths. Several flight modes were considered in water and mixed clouds at different altitudes.

![Figure 5](image)

**Figure 5.** Geometric model variants: (a) – wing; (b) – wing with engine nacelle; (c) – aircraft.

5.2. **Results**

As a result of parametric modelling, the values of pressure along the wing, temperature as a result of aerodynamic heating, the nature of the flow around the wing, and the time dependences of the duration of preparation and calculation for the various options considered are determined and analysed. It was established that at the initial stages of design it is rational to use only the aerodynamic surface of the wing. In this case, the difference will be no more than 7–10%, and time costs will decrease by 15–20%. To obtain the result in the shortest possible time, roughening the grid of finite volumes will reduce the calculation time by 10 times, and the loss in accuracy will be no more than 10%. Taking into account the diffuser and bypass of the engine at this stage of design affects the design characteristics insignificantly, both when considering separately a wing (2%) and the entire aircraft (1.5%). The mass, thickness, geometric shape of ice on the wing surface, and the aircraft were determined depending on the phase composition of the air, flight mode, angle of attack and altitude. It is shown that at the initial stages of the design of a wing made of carbon fibre reinforced polymer composite, the consideration of icing from the standpoint of strength has an indirect effect, a detailed consideration of this effect in the framework of the task gives an insignificant result.

6. **Determination of Carbon Fibre Wing Elements Parameters**

6.1. **Source data**

For the selected SA, the basic parameters of the carbon elements were optimized: the choice of thicknesses and the direction of layers. The SA consists of finned panels (skins reinforced by eleven stringers), two spars and fourteen ribs (Figure 6). The angles of attack varied: $0^\circ$, $+11^\circ$, $-7^\circ$. The simultaneous action of the following concentrated and distributed loads (the weight of structural elements, the weight of the engine, fuel, aerodynamic load) was considered. The total number of estimated cases exceeded 11,000.

6.2. **Results**

As a result of mathematical modelling for the choice of the SA element thicknesses, the deflection and mass of the structure and the optimal values of laying are determined.

7. **Topological Optimization**

7.1. **Source data**

The geometric model was a skin forming the theoretical surface of the wing and SA of the wing box: two spars, fifteen ribs, eleven stringers (for each skin). The SA of the leading-edge assembly and tail
parts of the wing were not taken into account. The root and end chords are 6 and 1.3 m, respectively. 

The effect of the loads was considered as when determining the parameters of the wing elements. Several design models are considered, both from an isotropic material (aluminium alloy) and from anisotropic (carbon fibre). Structures made of isotropic material were considered for: analysis of the selected SA, comparison with a wing made of anisotropic material, determination of critical zones, as well as zones of structural reinforcement during further wing design.

![Figure 6](image6.png)

**Figure 6.** The main elements of the SA wing for selecting reinforcement schemes (upper skin and stringers not shown): 1 – lower skin; 2 – rib; 3 – front spar; 4 – stringer; 5 – rear spar.

7.2. **Results**

As a result of optimizing the design of the wing and the power caisson under the action of operational loads at several angles of attack, the following were obtained and analysed:

- Material distribution over the volume of an isotropic material wing and individual power elements (Figure 7)
- Geometric characteristics of PCM wing elements with stackings different from quasi-isotropic with different pitch orientations of the layers
- The most loaded areas of the structure
- The geometric shape of the zones of reinforcement of structural elements

The use of piling with a large number of layers of different orientations allows reducing the weight of the finished product by adapting the reinforcement circuit to the existing loads while maintaining the structural displacement but can complicate the manufacturing technology.

![Figure 7](image7.png)

**Figure 7.** The results of an ultralight carbon fibre wing topological optimization to determine rational reinforcement zones:
(a) – original wing geometry;
(b) – material distribution after optimization.

8. **Tow-Steered Composites**

8.1. **Source data**

For the previously obtained wing with the SA, the possibility of using directional laying of fibres in the layers was considered.

The choice of reinforcement directions was carried out in two ways: zone and direction methods. For the zone method, the casing is divided into zones, the laying is determined for each individually.
For the direction method, the direction of action of normal stresses is determined, based on which calculation paths are modelled.

8.2. Results
As a result of parametric modelling, the following are defined:

- Angles for laying a prepreg based on a carbon tape in a layer in two different ways
- Stress-strain states under the action of operational loads for each option
- Optimal options for laying directions (Figure 8)

The section-by-section modelling allows obtaining layering, which gives a gain both in deflection (up to 8%) and in the damage ratio (on average, 1.5 times). Layering modelling based on the direction of action of normal stresses for finite elements can reduce the deflection of the structure by 12%, and the damage ratio by 1.3 times.

This part of the study can be considered the initial stage of research in the field of structurally optimized polymer composite wing structure, aimed at creating a universal design methodology. The results obtained will be used in further studies to determine the rational directions of the power structural layout elements, to create a method for choosing rational ways to lay out the PCM layers, aimed at improving the strength characteristics and aeroelastic properties of the wing.

![Figure 8. Laying in a layer: (a) – zone method; (b) – referral method.](image)

9. Conclusion
In accordance with the proposed universal methodology, the following individual tasks were completed:

- Aerodynamic loads were determined, based on parametric modelling of the external aerodynamics problem when flying at cruise, for 12 geometric wing models at different angles of attack. The following were established: rational geometric parameters for the wing taking into account sweep angles, transverse V and aerodynamic profile, and aerodynamic loads taking into account the possible formation of turbulent flows.
- The influence of the main elements of the aircraft in determining aerodynamic loads on the wing was analysed.
- The primary geometric model of the ultralight wing of a medium-range carbon fibre aircraft which meets the level of the outline design was determined.
- On the basis of the parametric modelling of 90 geometric models of SA wing, made of carbon fibre and at different angles of attack, the following were established: rational geometric parameters of SA wing - installation step and the number of ribs, stringers, spars, the shape and material of the power element of the panel – stringer.
- Using parametric optimization for elements of SA the following were defined: the rational minimum possible number of layers, optimal layer orientation angles, design deflection values for the selected optimal styling, and safety factors of structural elements.
- A topological optimization of the wing structure and individual elements was carried out.
- A variant of directional laying of fibres in layers was proposed.
The work will be expanded and supplemented by expanding the computational studies, experimentation and studies of additional factors affecting the wing.

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