Approach to optimization of composite aircraft wing structure

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Abstract. This paper describes an approach to optimization of composite aircraft wing structure basing on multi-criterion method. Two types of composite wing structures such as two-spar and three-spar ones were considered. The optimal layout of a wing frame was determined by Pareto optimization method basing on three criteria: minimal wing deflection, maximal safety factor and minimal weight. Positions of internal wing frame parts (spars and ribs) were considered as optimization parameters. As a result, an optimal design of a composite spar-type wing was proposed.

1. Introduction

The main technical requirements for the aircraft wing include weight, strength and rigidity of the structure. When solving practical problems of optimal wing design, one of these requirements, for example, weight can be considered as a criterion, and the other two - as limitations. In this case, the setting of the optimization problem is a single-criteria one. This approach was used in [1-4, 6, 7]. In [5], the authors of this article applied an approach based on two-criteria optimization of a two-spar composite wing. The criteria were considered to be the minimum weight and minimum deflection of the wing (maximum wing stiffness). The optimal orientations of the composite plies and the optimal thicknesses of the wing composite parts with a fixed position of the front and rear spars were determined in the study.

The purpose of this work was to determine the optimal structure of the wing frame using three optimization criteria: the minimum weight, the minimum deflection and the maximum wing safety factor under flight loads. Two variants of the wing frame were considered: two-spar and three-spar. The total thickness of the spars, as well as the thickness of the ribs and skin for both design schemes were considered as the same. Coordinates of the spars along the wing chord were considered as optimization parameters. It was supposed that location of spars was varied discretely. In this study, the composite wing of K-8 light aircraft was considered as an object of analysis. The stress-strain and buckling analysis of the wing were performed in a nonlinear static formulation using the FEMAP software package.
2. Formulation of the optimization problem

2.1. Configuration of the wing frame

The main structural elements of an aircraft wing are longitudinal frame parts of the wing – spars, transverse frame elements – ribs and a skin. Each element of the wing structure performs a specific function. In particular, one of the main functions of spars is to resist the bending moment that occurs when the wing is subjected to aerodynamic loads. Ribs form the profile of the wing and provide transverse stiffness of the skin. The skin provides the shape of the wing and its aerodynamic characteristics. There are a number of wing designs that differ in the number of spars. In this paper, an approach that allows to choose the optimal design scheme of the wing that meets several criteria was proposed. As an example, two variants of the wing frame were considered. In the first variant, the frame had two spars, in the second one three spars as shown in figure 1(a) and 1(b).

![Figure 1. (a) Two-spar wing model; (b) Three-spar wing model.](image)

The considered variants of the spar layout are presented in table 1.

| Parameters                             | Values | Total number of variants |
|----------------------------------------|--------|--------------------------|
| Position of front spar (% from the length of the wing chord) | 10% 15% 20% | Two-spar wing | Three-spar wing |
| Position of main spar (% from the length of the wing chord) | 40% 45% 50% | 27 | 81 |
| Position of back spar (% from the length of the wing chord) | 60% 65% 70% | | |
| Pitch length between of ribs, (mm) | 300 350 400 | | |

2.2. Aerodynamic load acting on a wing

In this study, the weight of wing of the K-8 light aircraft was $G_w = 606$ kg while the take-off mass was $G_0 = 4330$ kg. It was assumed that the safety factor of a light aircraft was $f = 1.5$, and the maximum operational overload coefficient was $n_{\text{max}} = 7.8$. In this regard, the aerodynamic wing load was calculated by using the following formulas [8],

\[
q_y = n_{\text{max}} \cdot f \cdot G_0 \cdot b(z)/S, \quad (1)
\]

\[
q_w = n_{\text{max}} \cdot f \cdot G_w \cdot b(z)/S, \quad (2)
\]

\[
q_s = q_y - q_w, \quad (3)
\]

\[
P_x = q_s/b(z), \quad (4)
\]
where $z$ - length of wing span; $b(z)$ - length of wing chord; $q_y$ - distributed lift force acting on the wing; $q_{w}$ - distributed structural load of the wing; $q_z$ - resulting aerodynamic load acting on the wing; $P_x$ - resulting distributed pressure acting on the wing (design pressure).

As a result of calculations, design pressure acting on the wing $P_x = 0.012$ MPa was obtained.

2.3. The choice of optimal layout of the wing

The composite wing optimization problem was considered as a two-criteria Pareto optimization. Two couple of criteria were taken as independent ones:

1. criteria for minimal mass and minimal deflection,
2. criteria for minimal mass and maximal margin of safety.

The coordinates of the spars and the distance between ribs were selected as optimization parameters. The optimal design of the wing in the plane of two criteria was determined by the "ideal center" method. The distance between two alternatives in the plane was defined as the Cartesian distance in dimensionless units of length:

$$R^i = \sqrt{\left(\frac{\delta_{w}^{i} - \delta_{w}^{0}}{\delta_{w}^{0}}\right)^2 + \left(\frac{G_{w}^{i} - G_{w}^{0}}{G_{w}^{0}}\right)^2} \to \min$$

$$R^i = \sqrt{\left(\frac{(k^{i} - k^{0})}{(k^{0})}\right)^2 + \left(\frac{G_{w}^{i} - G_{w}^{0}}{G_{w}^{0}}\right)^2} \to \min$$

where, $R^i$ – dimensionless distance between the $i$-th variant and the ideal center, $\delta_{w}^{i}$, $\delta_{w}^{0}$ – deflections of wing for the $i$-th variant and for the ideal center, $k^{i}$, $k^{0}$ – safety factors for the $i$-th variant and for the ideal center, $G_{w}^{i}$, $G_{w}^{0}$ – weights of wing for $i$-th variant and the ideal center.

3. Results and Discussion

3.1. Optimization of two-spar and three-spar wings

The stress-strain analysis of the wing was carried out for two variants of the construction: with two and three spars. The thickness of the skin, spars and ribs, as well as the lay-up angles of composite plies were determined by the same values as in the previous work [5]. The total thickness of the spars for two-and three-spar construction was considered as the same. There were considered 27 variants of the two-spar wing design and 81 variants of the three-spar wing design with variable parameters of the spar position and the distance between the ribs. The calculation results of mass and deflection of the wing are shown in table 2 and table 3.

### Table 2. Two-spar wing

| №  | Position of front spar (% from the length of the wing chord) | Position of back spar (% from the length of the wing chord) | Pitch length between of ribs, (mm) | Maximal deflection, (mm) | Weight of wing, (kg) |
|----|-----------------------------------------------------------|-----------------------------------------------------------|----------------------------------|------------------------|---------------------|
| 1  | 10                                                        | 60                                                        | 300                              | 55.04                  | 83.79               |
| 2  | 10                                                        | 65                                                        | 300                              | 56.06                  | 83.32               |
|    | -                                                         | -                                                         | -                                | -                      | -                   |
| 13 | 15                                                        | 60                                                        | 350                              | 54.32                  | 83.60               |
| 14 | 15                                                        | 65                                                        | 350                              | 55.11                  | 83.13               |
|    | -                                                         | -                                                         | -                                | -                      | -                   |
| 26 | 20                                                        | 65                                                        | 400                              | 54.31                  | 82.39               |
| 27 | 20                                                        | 70                                                        | 400                              | 55.37                  | 81.86               |
Table 3. Three-spar wing

| №.  | Number of variant | Position of front spar (% from the length of the wing chord) | Position of front spar (% from the length of the wing chord) | Pitch length between of ribs, (mm) | Maximal deflection, (mm) | Weight of wing, (kg) |
|-----|------------------|-------------------------------------------------------------|-------------------------------------------------------------|-----------------------------------|------------------------|---------------------|
| 1   | 10               | 40                                                          | 60                                                          | 300                               | 51.65                  | 85.03               |
| 2   | 10               | 40                                                          | 65                                                          | 300                               | 51.54                  | 84.75               |
|     | -                | -                                                           | -                                                           | -                                 | -                      | -                   |
| 44  | 15               | 45                                                          | 65                                                          | 400                               | 49.1                   | 83.78               |
| 45  | 15               | 45                                                          | 70                                                          | 400                               | 49.62                  | 82.72               |
|     | -                | -                                                           | -                                                           | -                                 | -                      | -                   |
| 80  | 20               | 50                                                          | 65                                                          | 400                               | 50.94                  | 83.06               |
| 81  | 20               | 50                                                          | 70                                                          | 400                               | 50.76                  | 82.73               |

Alternative variants for two- and three-spar wings are shown in figure 2(a) and 2(b) as points on the plane of criteria (weight - deflection). The set of non-dominant Pareto alternatives included 7 alternatives for a two-spar wing (8, 9, 19, 22, 25, 26, and 27) and 6 variants of the three-spar wing (27, 45, 54, 77, 78 and 81).

![Figure 2](image)

**Figure 2.** Alternatives in the weight-deflection criteria plane: (a) two-spar wing, (b) three-spar wing.

Each alternative was evaluated by the distance to the ideal center to determine the one with the smallest distance. The calculation results of these distances are shown in table 4.

Table 4. Dimensionless distances between Pareto alternatives and the ideal center

| № of variant | Dimensionless distance | № of variant | Dimensionless distance |
|--------------|------------------------|--------------|------------------------|
| 8            | 0.058                  | 27           | 0.031                  |
| 9            | 0.086                  | 45           | 0.021                  |
| 19           | 0.047                  | 54           | 0.029                  |
| 22           | 0.038                  | 77           | 0.031                  |
| 25           | 0.026                  | 78           | 0.025                  |
| **26**       | **0.025**              | **81**       | **0.017**              |
| 27           | 0.035                  | -            | -                      |
The results presented in table 4 showed that alternative 26 is optimal for a two-spar wing, while variant 81 is optimal in the case of three-spar. In addition, other several alternatives were found showing rather similar results in both cases. Therefore, to clarify the optimization results, the second pair of criteria was considered: minimum weight and maximum margin of safety. The values of the criteria were determined based on the results of buckling analysis of the wing. Calculations were performed using a static nonlinear model with stepwise loading of the wing. Such a loading continued until the ultimate load at which the wing was in a state of static equilibrium was reached. It was shown that the maximum load did not reach the design pressure value (0.012 MPa) for variants 8, 9 and 26 (two-spar wing) and 27 and 77 (three-spar wing). These alternatives were therefore excluded from further consideration. The results of these calculations are presented in figure 3(a) and 3(b).

Figure 3. Nonlinear wing deflection vs stepwise increasing load for Pareto optimal alternatives (a) two-spar wing, (b) three-spar wing.

The field of alternatives for the second set of criteria is shown in figure 4(a) and (b). As a result of comparing the distances to the ideal centers, the optimal wing variants were finally established: variant 27 for a two-spar wing and variant 45 for a three-spar wing.

Figure 4. Alternatives in the weight-safety factor criteria plane: (a) two-spar wing, (b) three-spar wing.

3.2. Stress analysis of the wing optimal variants
As verification calculations, the analysis of the strength under the action of the ultimate load for each optimal variant was carried out.
Namely, for variant 27 (two-spar wing), the load was equal to 0.017 MPa, and for variant 45 (three-spar wing), a load of 0.02 MPa was applied. The results presented in figure 5 clearly showed that the current maximum stresses did not exceed the ultimate strength of the composite layer of 1400 MPa in each of the wing structural part. It should be noted that the safety factor for the design pressure for two-spar wing was 1.45 and for the three-spar one 1.67.

3.3. Comparing two alternatives based on three criteria

Previously, for the two alternatives remaining in consideration: variant 27 (two-spar wing) and 45 (three-spar wing), the values of the maximum deflection of the wing, characterizing the rigidity of the construction, as well as the value of the safety coefficient, characterizing the reliability of the structure, were determined. The value of the third criterion - the weight of structural elements and the wing as a whole are presented in table 5.

### Table 5. Weight for two-spar wing and three-spar wing

| №. | Structural elements | Two-spar wing | Three-spar wing |
|----|---------------------|--------------|----------------|
| 1  | Skin                | 68.15        | 68.15          |
| 2  | Front spar          | 3.84         | 1.72           |
| 3  | Middle spar         | -            | 4.39           |
| 4  | Back spar           | 3.53         | 2.11           |
| 5  | Ribs                | 6.34         | 6.34           |
| 6  | Total weight        | 81.86        | 82.72          |

The values of all three criteria are presented in table 6.

### Table 6. Optimization criteria values

| Criterion                           | Two-spar wing, variant 27 | Three-spar wing, variant 45 | Deviation, (%) |
|-------------------------------------|----------------------------|-----------------------------|----------------|
| Weight, (kg)                        | 81.9                       | 82.7                        | 1              |
| Deflection under design pressure, 0.012 MPa, (mm) | 140                        | 100                         | 40             |
| Safety coefficient                  | 1.45                       | 1.67                        | 14             |

Comparing the differences in the values of all three criteria, preference should be given to the three-spar version of the wing with design parameters corresponding to variant 45.
4. Conclusions
The main results of this study can be formulated as follows:

- An approach to the rational choice of composite wing parameters was proposed,
- Optimal variants of construction for two- and three-spar wings were determined,
- The optimal design of a composite spar-type wing was proposed based on multi-criteria optimization.

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