Design of a structurally optimized bioinspired structural arrangement of a polymer composite regional aircraft tail fin

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Abstract. Aircraft frame elements are highly responsible elements. They are subject to stringent requirements for strength, stability, resource. Often these requirements contradict each other, especially if it is necessary to ensure the minimum mass of the product. However, it is necessary to improve the characteristics of aircraft. Nevertheless, the optimization of the frame has almost exhausted itself. The power frame consists of longitudinal and transverse elements. It is possible to improve the characteristics of structural arrangement by using polymer composite materials based on glass and carbon fibers. This will improve the design characteristics due to high specific properties. In addition, one of the directions is the development of new bioinspired structural layout based on natural analogues. The work is devoted to the actual task of searching and choosing new structural arrangement for the aircraft tail. The paper considers five variants of structural layout, including the classical original design. The advantage of the bioinspired variant in terms of mass and displacement is shown.

1 Introduction

To develop a structural arrangement, it is necessary to take into account many factors [1-2]. A complex design problem is solved taking into account aerodynamics, stability, and strength [3]. The simultaneous consideration of a set of aggregate parameters is taken into account. The quantity, location, shape and material of the elements of the power circuit are selected [4-5]. Restrictions are also imposed by the methods of manufacturing parts. The development of additive technologies [6], in particular from polymer composite materials [7-8], makes it possible to manufacture products that were previously inaccessible [9]. Such structures include bioinspired structural arrangement based on natural analogs – the direction of installation, shape, quantity, orientation in space of power elements is similar to biological analogous objects, for example, insect wings [10]. In addition, the use of polymer composite materials [11-12] can significantly improve the specific characteristics of the part and the structure as a whole [13]. Structural arrangement with rectilinear load-bearing elements, longitudinal and transverse directions of installation become possible to replace with new curvilinear schemes [14-15] and biosimilar structures [16]. Complex

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layouts are created using parametric [17], topological optimization [18] methods and are made by 3D printing [19]. This makes it possible to reduce the weight of the product without loss in strength properties [20, 21]. The reinforcement schemes of the product, in turn, are adapted to the existing loads [22]. The developed structural layout with curvilinear bioinspired spars and ribs are optimized by various methods [23] for all possible loads in various flight modes [24]. Such layout can be used for a wide range of objects, such as wings, horizontal and vertical tail [25]. Methods for calculating and determining such structures are being developed [26]. Thus, it is logical to state that the use of fundamentally new structural layout to meet the ever-increasing requirements for polymer composite structures is an urgent task.

2 Source data

2.1 Subject of research

The tail fin of the aircraft (Figure 1) with the parameters (Table 1) was considered as the object of study.

Table 1. Main parameters of tail fin

Parameter	Value
height	5,2 m
root chord length	4 m
end section chord length	1,7 m
sweep angle	40°;
surface area	14,8 m^2
airfoil	symmetric

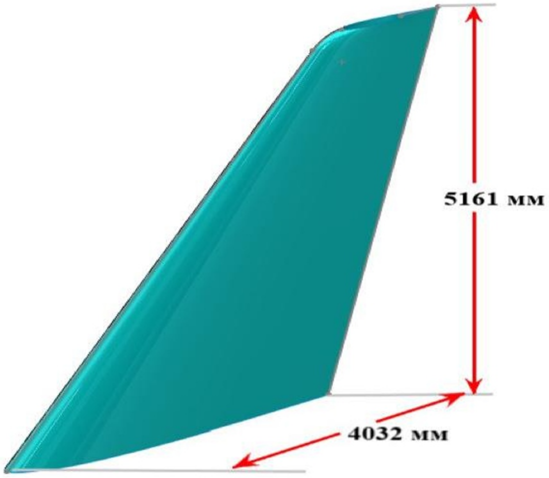


Fig. 1. The appearance of the tail fin

The main structural materials are carbon fiber and fiberglass based on unidirectional tapes (Table 2). An aluminum alloy was also considered for comparison.

Table 2. Physical and mechanical characteristics of the materials

Parameter		**Fiberglass**	**Carbon**	**Aluminium**
Density, kg/m^3		2000	1550	2700
Elasticity modulus, GPa	Along the fiber	37,2	50,6	70
	Across the fiber	26,0	35,4	
Shear elasticity, GPa		21,7	29,7	27
Tensile strength, MPa	Along the fiber	352,6	483	390
	Across the fiber	49,0	67,0	
Compressive strength, MPa	Along the fiber	202	297	390
	Across the fiber	78	107	

3 Loads on the structures

The following loads were considered:
- airload;
- own weight of the unit and payload weight of 30 kg;
- concentrated weight of rudder controls.

The calculation of loads was carried out for a maneuver an aircraft at a speed of 218 m/s for a turn in an arc of 180 m, at an altitude of 6 km (turn).

The calculation of the airload was carried out in the Ansys software package, in the CFX module, taking into account the flight parameters (speed, angle of attack) and atmosphere (Figure 2, 3). The calculations were carried out in a stationary mode with the accuracy of the solution 10^{-4}.

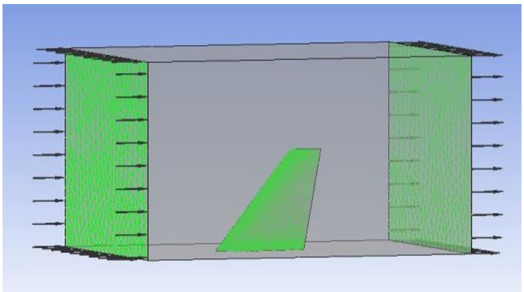


Fig. 2. Calculation model

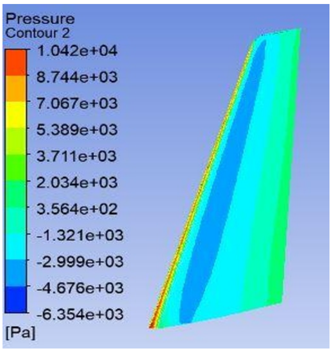


Fig. 3. Distribution of aerodynamic pressure on the surface of the tail fin, Pa

4 Structural layout of tail fin

Five different structural arrangement of two types were designed and considered.

As the initial design, a two-spar tail fin with twelve ribs located perpendicular to the front spar was considered (Figure 4).

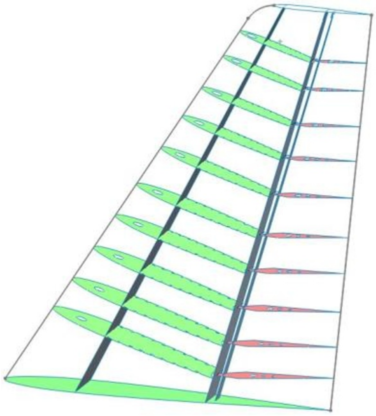
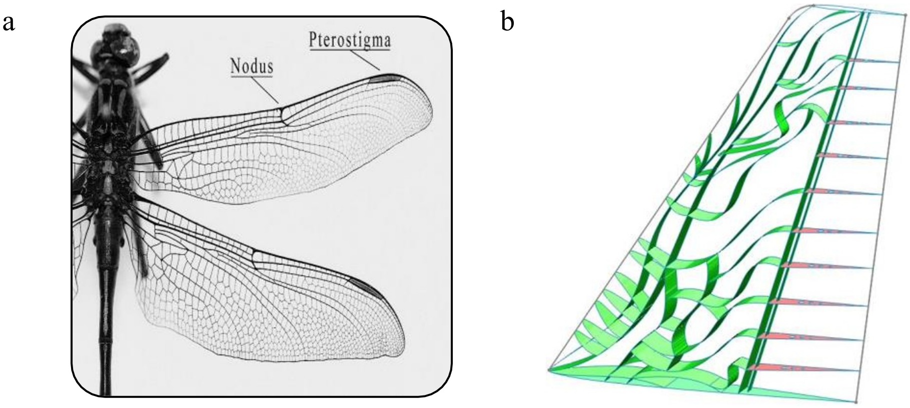


Fig. 4. The original structural layout of the tail fin

Bioinspired structural layout are based on insect wings and honeycombs [27-29]. The main considered species were the wings of the Odonata, Hymenoptera, Anthophila, Coleoptera and Melolonthina, as well as honeycombs (Figure 5).



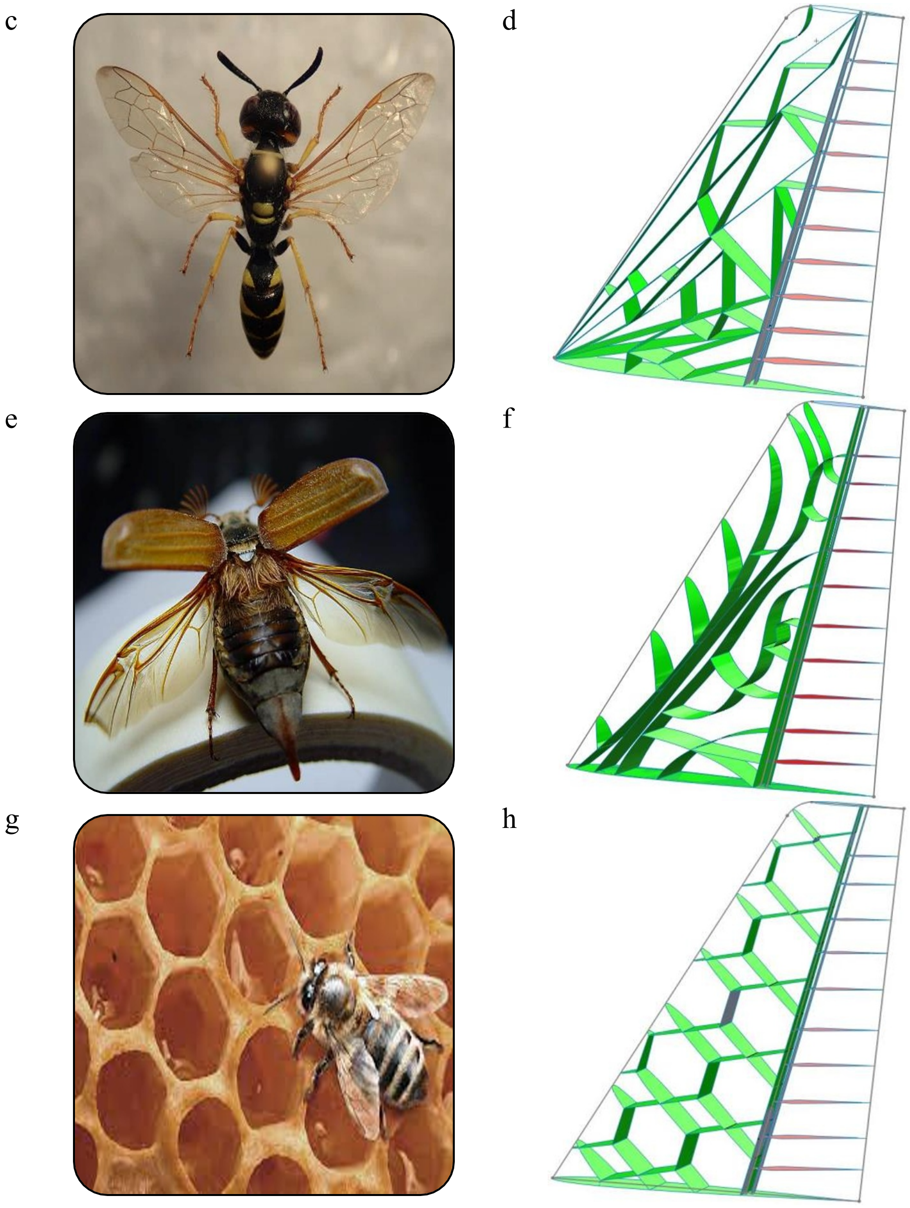


Fig. 5. Bioinspired structural layout (SL) of tail fin: (a) – Odonata wing; (b) – SLA based on Odonata; (c) – Anthophila wing; (d) – SL based on Anthophila; (e) – Melolonthina wing; (f) – SL based on Melolonthina; (g) – honeycomb; (h) – SL based on honeycomb;

5 Calculation results

For five variants of power circuits, the stress-strain state under the action of the load was determined. As a result, the mass, deformation, stresses in the structure were compared and analyzed.

The tensile strength of the material in all the considered structures is not exceeded. The safety factor is greater than 1.5, which indicates the possibility of further optimization of all schemes. An exception is the silt scheme based on honeycombs. Despite the smallest mass, the tensile strength is quite low and close to 1. This is due to the absence of a solid element along the entire span of the keel.

Figure 6 shows the results of the distribution of options for two parameters (mass, deformation).

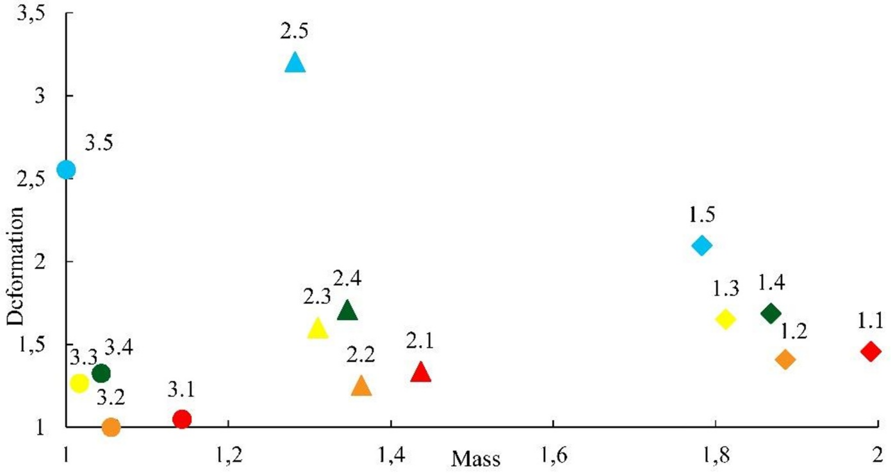


Fig. 6. Variants distribution by mass and deformation in relative values from materials: ♦ – aluminium, ▲ – fiberglass, ● – carbon

Show the distribution of options by groups. This is due to the density of materials. The closest to the ideal center are options and from carbon fiber.

The optimal structural arrangement, from the obtained ones, can be determined both by introducing an additional parameter, for example, cost, and by choosing the shortest distance to the theoretical center (TC) according to the equation (1):

$$K = \left[\frac{(m_{TC} - m_i)^2}{m_{AM}^2} + \frac{(d_{TC} - d_i)^2}{d_{AM}^2} \right]^{1/2}$$

where m_{TC}, d_{TC} — TC mass and deformation values, m_i, d_i — variant mass and deformation values, m_{AM}, d_{AM} — arithmetic mean mass and deformation values.

Of options 3.2 and 3.3 based on the wings of an Odonata and an Anthophila, respectively, the first one is closest to the TC. Its mass is 165.5 kg, which is two times less (53%) than the metal counterpart and 10% less than the carbon fiber keel.

6 Conclusion

The paper considers promising bioinspired variants of the structural arrangement of the tail fin, which make it possible to increase the specific design indicators.

Curvilinear elements show better characteristics compared to straight ones in terms of achieving greater structural efficiency of the wing under the action of operational loads in various flight modes.

It has been established that polymer composite bioinspired structural layout outperform classical metal structural layout by up to 50% by weight and can be further optimized. The mass gain compared to the classical structural layout made of composite materials is about 10%.

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