Research of the Materials and Reinforcement Schemes Effects on a Mechanical Behavior Smart Structure with Embedded Piezo Actuators

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Abstract. The present work is devoted to the research of a helicopter blade segment stress-strain state. The segment was made of polymer composite materials with embedded piezoelectric actuators. The computational model of the blade segment takes into account the technological order of laying and the anisotropy of the reinforcing layers properties. The reinforcement schemes under consideration were [0°/90°], [45°/-45°], [0°/45°/-45°/90°]. The static strength margin was estimated using the criterion of maximum stresses. A layered analysis of the structure stress-strain state was carried out. It was shown that the most dangerous, determining the structure margin of safety, are normal interlayer stresses. It was found that the GFRP material and the structural reinforcement scheme [0°/90°], selected during the design, provide the greatest torsion angles.

1. Introduction

Recently, in aeronautical engineering, there has been a tendency to use SMART structures with controlled geometry. This allows to significantly improve the aircraft operational characteristics by reducing the vibro-acoustic loading of highly loaded elements such as an airplane wing or helicopter blades [1]. The development of SMART structures from PCM equipped with piezoelectric elements, on the one hand, will reduce the weight of the structure, and on the other hand will eliminate mechanical drives and swashplates, which will significantly reduce the cost of servicing structures with controlled geometry and aircraft fuel consumption.

With the greatest efficiency, SMART designs can be used to create aircraft wings with variable geometry, which will optimally adapt to the aerodynamic parameters of the airflow [2]. The application of SMART technologies to damping oscillations by helicopter blades is considered. Currently, the possibility of applying SMART technologies to create fan blades and an aircraft engine straightening apparatus is being considered [3].

Currently, some works are known that describe the theoretical foundations of creating PCMSMART structures with controlled geometry [4,5]. Numerical models of the blade cross-section have been developed and parametric studies of the controlled structure equipped with AFC actuators relative stiffness have been carried out to determine the optimal configuration of the blade.

In [6], numerical results for a four-blade bearingless rotor model with self-tuning piezoelectric actuators located at an angle of 45° on the upper and lower surfaces of the composite blade were presented. To analyze the dynamic loads on the main rotor with composite blades, a complex model
was developed. To model the behavior of a layered structure made of smart composite, an approach based on the theory of high-order deformation was used [7].

In [8-10], a series of works was carried out related to the analysis of the structural and aerodynamic parameters of the rotor blades in order to better understand the effect of active twisting. The influence of the blade active twisting, the required power, the load on the blade and the hub were evaluated in relation to the change in stiffness (torsional and bending in the planes of the swing and rotation), sectional mass and torsion inertia, the center of gravity and the location of the blade elastic axis. However, the scientific problem limiting the SMART constructions development (implementation in engineering design practice) is the lack of scientifically based approaches and proven methods for their design. To solve this problem, it is necessary to carry out a set of computational and experimental studies aimed at developing new mathematical models of composite materials with piezoelectric structural elements (piezocomposites), at developing methods for solving related boundary problems of electromagnetically elasticity for inhomogeneous media with piezoelectric structure elements. There is a need to design methods for calculating structures, choosing control elements, concept development, calculation methods, creating methods for designing structures, testing models and methods using structurally similar SMART structures samples, development of experimental technologies for their manufacture from modern materials, and testing these prototypes.

The present work is devoted to a controlled helicopter blade segment stress state analysis. A research was carried out of the reinforcement scheme and materials influence on the blade segment mechanical behavior using piezo thermal analogy, as well as an assessment of the strength under operational loads.

2. Numerical model

The object of this study is a controlled helicopter blade segment with embedded piezoelectric actuators. To conduct a numerical simulation of the stress-strain state, a three-dimensional computer model was developed with an explicit description of the layered structure. The geometric model includes a C-shaped spar, balancing weight, laminated Sheathing, foam filler, embedded element and piezoelectric actuators located on the blade Sheathing. At the end of the blade is a steel fastener. The NACA 23012 profile was used as the aerodynamic profile. The geometric characteristics of the helicopter blade segment are shown in Figure 1 a. The segment length is 805 mm, the chord length is 121 mm.

![Figure 1. General view of the blade segment: a - the cross section of the blade segment; b - the geometric model of the blade segment.](image)

The following materials were considered as blade segment materials: 1) Glass Fiber Reinforced Polymer (GFRP); 2) Carbon Fiber Reinforced Polymer (CFRP). The blade segment Sheathing
consisted of four layers of GFRP or CFRP. Reinforcement schemes were \([0^\circ/90^\circ], [45^\circ/-45^\circ], [0^\circ/45^\circ/-45^\circ/90^\circ] \). Table 1 shows the considered variants of the blade segment samples.

Table 1. Variants of materials combinations of the blade segment samples.

| №  | Spar material | Sheathing material |
|----|---------------|--------------------|
| 1  | CFRP          | CFRP               |
| 2  | CFRP          | GFRP               |
| 3  | GFRP          | GFRP               |

Technical elastic constants of microfiber piezoelectric actuator (MFC) were taken from [11]:

- MFC – \( E_x = 30 \) HPa, \( E_y = E_z = 15.5 \) HPa, \( G_{xy} = G_{xz} = 10.7 \) HPa, \( G_{yz} = 5.7 \) HPa, \( v_{xy} = v_{xz} = 0.44, v_{yz} = 0.35, d_{31} = d_{32} = -1.98*10^{-10} \) m/V, \( d_{33} = 4.18*10^{-10} \) m/V.

As part of the computational experiments, the mechanical behavior of helicopter blade segments equipped with piezo actuators and made of GFRP and CFRP were simulated. The maximum axial displacements of the helicopter blade segment were calculated at a control voltage level of 1000 V. The solution of the problem was carried out by the finite element method using thermal analogy. Thermoanalogue allows to move from the need to solve the connected boundary value problem of electroelasticity to the solution of a much simpler unconnected boundary value problem of thermoelasticity. While stating the mathematical formulation, the hypothesis of the invariance of an electric inhomogeneous field in a piezoelectric element (arising from the action of a control electric voltage on its electrodes) was accepted. The hypothesis assumes the presence of a “reverse piezoelectric effect” in a piezoelectric element in the absence of a “direct piezoelectric effect” [12–14].

The strength assessment of the PCM helicopter blade segment was carried out according to the criterion of maximum stresses. This criterion was used to solve problems of this kind in [15, 16] and its choice is due to the lack of reliable data on the strength of the GFRP material under conditions of a difficult stress state.

The strength of the orthotropic material corresponds to the satisfaction of the system of inequalities at each point in the structure:

\[
S_{11}^- \leq \sigma_{11} \leq S_{11}^+ , \quad S_{22}^- \leq \sigma_{22} \leq S_{22}^+ , \quad S_{33}^- \leq \sigma_{33} \leq S_{33}^+ , \quad S_{12} \leq \sigma_{12}, \quad S_{13} \leq \sigma_{13}, \quad S_{23} \leq \sigma_{23},
\]

where \( S_{ii}^+, S_{ii}^- \) are the limits of the material’s static tensile, compression, and shear strengths, respectively, in the local coordinate system of the layer.

Safety margin of equal strength GFRP for various components of the stress state was estimated by the equation:

\[
n_{ij} = \min_{\text{rev}} \left( \frac{S_{ij}}{\sigma_{ij}(r)k} \right),
\]

where \( k \) is the coefficient of decrease in the static strength of the material due to the influence of various environmental factors.

The \( n_{ij} \) minimum value for all \( \sigma_{ij} \) components will determine the margin of safety of the controlled helicopter blade segment.

3. Results of numerical modeling

Based on the results of numerical modeling of mechanical behavior under the action of a 1000 V control voltage, the fields of stresses and displacements for a helicopter blade segment made of GFRP and CFRP were obtained. Figure 2 shows the axial displacement distribution fields \( U_y \) of the blade segment.
Figure 2. Fields of distribution of the blade segment displacements: a - GFRP and CFRP; b - CFRP; c - GFRP.

An analysis of the axial displacement fields $U_y$ revealed that the maximum torsion angle was obtained for the GFRP helicopter blade segment. Table 2 presents the value of the helicopter blade segment torsion angles.

Table 2. Results of numerical simulation.

| №  | Spar material | Sheathing material | Torsion angle, ° |
|----|---------------|--------------------|-----------------|
| 1  | CFRP          | CFRP               | 0.57            |
| 2  | CFRP          | GFRP               | 1.15            |
| 3  | GFRP          | GFRP               | 1.33            |

It was found that the use of GFRP in the design of the blade segment provides the greatest torsion angles. The difference between the values of the torsion angles of the GFRP and CFRP blade segment is 57.14%. At the same time, the blade segment with the spar made of CFRP exhibits minimal longitudinal deformations. Thus, as a material, for the manufacture of a controlled helicopter blade segment with embedded piezoelectric actuators, an equal-strength GFRP is proposed.

At the next stage of the work, a numerical study of the effect of reinforcement schemes on the mechanical behavior of the blade segment was carried out. Based on the results of numerical simulation, the fields of stresses and displacements for a blade segment with embedded piezoelectric actuators were obtained. Figure 3 shows the axial displacement distribution fields $U_y$ of the segment of the controlled helicopter blade at a control voltage of 1000V for the three reinforcement schemes.

Figure 3. Fields of distribution of blade segment displacements with a reinforcement scheme: a - [0°/90°]; b - [45°/-45°]; c - [0°/45°/-45°/90°].
An analysis of the Uₙ axial displacements revealed that the largest torsion angles for the controlled helicopter blade segment sample from GFRP were observed for the reinforcement scheme [0°/90°]. Table 3 presents the results of numerical modeling of the blade segment mechanical behavior.

**Table 3.** The results of numerical simulation of the blade segment mechanical behavior.

| № | Reinforcement scheme | Torsion angle, ° |
|---|----------------------|-----------------|
| 1 | [0°/90°]             | 2.12            |
| 2 | [45°/-45°]           | 1.333           |
| 3 | [0°/45°/-45°/90°]    | 1.585           |

According to the results of numerical modeling, it was found that when using the reinforcement scheme [0°/90°], an increase in the torsion angle value is observed compared with the reinforcement schemes [45°/-45°] and [0°/45°/-45°/90°] by 37.12% and 25.24% respectively.

When designing a GFRP torsion structure, it is recommended to use the reinforcement scheme [0°/90°]. At the same time, in order to meet the requirements for this class of construction, it is necessary to assess the strength of the structure under operational loads at extreme angles of attack (12°).

To conduct a preliminary strength assessment, numerical calculations of the stress strain state of the segment were performed under the action of operational loads (lifting force Y + = 147.1 N, for an angle of attack of 12°). According to the results of numerical modeling of mechanical behavior under the action of operational loads, the distribution of stress and displacement fields was obtained for a blade segment with embedded piezoelectric actuators.

Analysis of the distribution of stress fields in the directions of layers reinforcing along the base and the weft in the coordinate system of the structure showed that they reach the greatest value in the region where the blade segment was attached. The concentration zones of these stresses were located in the area of attachment of the metal grip on the upper part of the blade segment Sheathing. Moreover, the maximum values of these stresses occurred on the surface of the outer layer of the blade Sheathing. The maximum normal tensile stresses along the base were σ₁₁ = 78.581 MPa, along the weft σ₂₂ = 54.276 MPa, and the maximum compressive stresses were σ₁₁ = -74.155 MPa and σ₂₂ = -61.161 MPa, respectively.

The maximum values of normal interlayer stresses were observed in the area of the leading edge between the first and second layer of the blade segment Sheathing. The compressive stresses σ₁₁ reached an absolute value of 34.375 MPa, and the tensile stresses σ₁₁ reached a value of 10.165 MPa. The maximum values of the interlayer tangential stresses τ₁₁ were observed under a metal grip. The maximum tangential stresses were τ₁₁ = 37 MPa.

For tangential stresses τ₁₂ and τ₁₃, concentrations were observed near the metal fastening. The maximum value of tangential stresses in the reinforcement plane τ₁₂ was 13.571 MPa. The maximum value of the interlayer tangential stresses τ₁₃ was 19.548 MPa.

Assessment of the blades static strength was carried out according to the criterion of maximum stresses (1). The values of the static strength of the equal strength GFRP are given in table 4. The data presented was obtained experimentally, with the exception of the strength characteristics across the S₁₁ layer, the estimated values of which are taken from [16].

**Table 4.** Values of permissible normal and tangential stresses.

| S₁₁⁺ | S₁₁⁻ | S₂₂⁺ | S₂₂⁻ | S₁₃⁺ | S₁₃⁻ | S₁₂⁺ | S₁₂⁻ | S₁₃⁺ | S₁₃⁻ |
|------|------|------|------|------|------|------|------|------|------|
| MPa  | MPa  | MPa  | MPa  | MPa  | MPa  | MPa  | MPa  | MPa  | MPa  |
| 410  | 320  | 410  | 320  | 44   | 128  | 150  | 70   | 70   |

The assessment made it possible to determine the static strength reserves of the blade segment structure by the stresses in the layers. Margin of safety calculated by the ratio (2) are presented in table 5.
Table 5. Margin of safety coefficients.

| $k_{11}^+$ | $k_{11}^-$ | $k_{22}^+$ | $k_{22}^-$ | $k_{33}^+$ | $k_{33}^-$ | $k_{12}$ | $k_{13}$ | $k_{23}$ |
|------------|------------|------------|------------|------------|------------|---------|---------|---------|
| MPa        | MPa        | MPa        | MPa        | MPa        | MPa        | MPa     | MPa     | MPa     |
| 5.22       | 4.32       | 7.55       | 5.23       | 4.33       | 3.72       | 11.05   | 1.89    | 3.58    |

Thus, at operational loads, the most dangerous in the design of the PCM blade segment are normal interlayer stresses. The margin of static strength of the GFRP blade segment is determined by these stresses and is 1.89.

4. Conclusion
As part of the research, a mathematical and numerical model for calculating the stress strain state of the controlled helicopter blade segment were developed. The choice of material and reinforcement scheme of the developed blade segment was made. It was revealed that when using the GFRP material and the reinforcement scheme [0°/90°], the largest torsion angle was observed, which amounted to 2.12°. Analysis of stresses in the layers of the helicopter blade segment revealed that the most dangerous, determining the margin of safety of the structure, are the normal interlayer stresses in the area. The margin of static strength of the GFRP blade segment at ultimate operating loads was 1.89.

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