Development of a structurally similar element of a helicopter blade with an active twist system

A N Anoshkin¹, E Barkanov², P V Pisarev³ and V A Ashikhmin¹,*

¹Perm National Research Polytechnic University (PNRPU), Komsomolsky Prospect, 29, Perm, Russia
²Riga Technical University, Kalku Str. 1, LV-1658, Riga, Latvia
*vladash96@gmail.com

Abstract. A mathematical model is formulated for calculating the stress-strain state (SSS) of piezoelectric layered polymer composite materials (PCM) equipped with a control piezo-actuator. The model implements the principle of thermo-piezoelectric analogy, which allows to move from the coupled boundary value problem of electroelasticity to the boundary value problem of thermoelasticity. The mathematical model was tested with a numerical calculation of the mechanical behavior of a sample structurally similar to a rotor blade, equipped with control piezo-actuators and made of equal strength and unidirectional fiberglass.

1. Introduction

There is a recent trend of using SMART structures with controlled geometry in aviation technologies. SMART structures make it possible to significantly improve the aircraft performance by reducing the vibroacoustic loading of highly loaded elements, such as an airplane wing or helicopter blades [1]. The development of SMART structures made of PCM equipped with piezoelements on the one hand will reduce the weight of the structure, and on the other hand will eliminate mechanical drives and skew automatons, which will significantly reduce the cost of maintaining structures with controlled geometry and fuel consumption of an aircraft.

SMART designs can be most efficient while developing new aviation wings with variable geometry, which will allow optimal adaptation to the aerodynamic parameters of the air flow [2]. The application of SMART technologies to damping oscillations of helicopter blades is now being considered as well (Figure 1). The possibility of using SMART-technologies in the creation of fan blades and an air engine rectifier apparatus is also under consideration [3].

There are some scientific works describing the theoretical foundations of creating SMART structures from PCM with controlled geometry [4, 5]. Numerical models of the blade cross section have been developed, and to identify its optimal configuration, parametric studies of the relative rigidity of the controlled structure equipped with AFC actuators have been carried out.
Figure 1. Examples of the SMART structures application (a) airplane wing profile with variable geometry (b) helicopter blade with variable geometry

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

In [8–10], a series of works was carried out related to the analysis of the structural and aerodynamic parameters of rotor blades in order to better understand the effect of active twisting. The influence of the active twisting of the blade, the required power, the load on the blade and the hub were evaluated in relation to changes in stiffness (torsional and flexural in the swing and rotation planes), sectional mass and torsion inertia, center of gravity and location of the elastic axis of the blade.

However, the scientific problem limiting the creation of SMART structures (introduction into the practice of engineering design) is the lack of scientifically based approaches and proven methods for their design. To solve this problem, it is necessary to carry out a complex of simulation and experimental studies aimed at developing new mathematical models of composite materials with piezoelectric structural elements (piezocomposites), and developing methods for solving related boundary problems of electro-magnetic elasticity for inhomogeneous mediums with piezoelectric structure elements. There is a need to develop methods for calculating structures, choosing the control elements, developing concepts, calculation methods, creating methods for designing structures, testing models and methods using structurally similar element for SMART structures, developing experimental technologies for their manufacture from modern materials, testing these prototypes.

In this study, new mathematical models of composite materials with piezoelectric structural elements (piezo composites) have been developed. The mathematical model was tested with the numerical calculation of the mechanical behavior of a sample structurally similar to a rotor blade equipped with piezoelectric actuators and made of equal strength and unidirectional fiberglass.

2. Numerical model
For the stress-strain state numerical simulation of the helicopter blade segment equipped with piezoactuators, a three-dimensional computer model was developed with an explicit description of the layered structure. The model consists of a spar, balancing load, plating, foam filler, as well as piezoactuators located on the sample plating. The geometrical characteristics of the helicopter blade segment are shown in Figure 2 a. The segment length is 1 m, the chord length is 121 mm. The NACA 23012 profile was used as an aerodynamic profile. The problem was solved using the finite element method (FEM) with the implementation of the ANSYS Workbench software package.

The following materials were considered as the covering material: 1) ACM102-G290P equal strength glass prepreg; 2) ACM102-G300UD unidirectional glass prepreg. The sample covering consists of 4 layers of glass prepreg with a reinforcement scheme [45°/-45°]. The technical elastics of the micro fiber piezoactuator (MFC) were taken from [13, 14]:

- MFC – $E_x = 30$ GPa, $E_y = E_z = 15.5$ GPa, $G_{xy} = G_{xz} = 10.7$ GPa, $G_{yz} = 5.7$ GPa, $\nu_{xy} = \nu_{xz} = 0.44$, $\nu_{yz} = 0.35$, $d_{31} = d_{32} = -1.98 \times 10^{-10}$ m/V, $d_{33} = 4.18 \times 10^{-10}$ m/V.
Figure 2. General view of the sample a) cross-section of the sample; b) a geometric model of the sample.

Also in the course of numerical modeling, convergence was studied. For better convergence of the solution and to reduce the errors of the results obtained, a computational grid was generated, the cells of which had a prismatic shape. The maximum element size was set to 3 mm, the minimum was 75*10^-3 mm. Additionally, when constructing and local grinding of the grid, no sharp differences in the geometric dimensions of adjoining elements were allowed.

As part of the computational experiments, the mechanical behavior of the segments of a helicopter blade equipped with piezoactuators and made of equal strength and unidirectional glass prepregs was modeled. The maximum axial movements of the helicopter blade segment were calculated at a control voltage level of 1000 V. To describe the inverse piezoelectric effect in the framework of the developed mathematical model, it is proposed to use a thermo-piezoelectric analogy between piezoelectric and thermoinduced deformations.

The analogy makes it possible to move from the need to solve a coupled boundary value problem of electroelasticity to the solution of a substantially simpler unrelated boundary value problem of thermoelasticity and is based on the hypothesis of invariance of an electrically inhomogeneous field in a piezoelectric element (arising from the action of a control electrical voltage on its electrodes) to deformation fields inside the volume of the piezoelectric element and, as a result, to the deformation of the structure, on the surface of which the piezoelectric element (piezoactuator) is fixed. That is to say, the hypothesis suggests the presence of the “inverse piezoelectric effect” in the piezoelectric element in the absence of the “direct piezoelectric effect”. Such an assumption is admissible for the cases when the “controlling” component of the electric field in the piezoelectric element, caused by the action of the control electric voltage $U_{\text{cont}}$ on the electrodes of the piezoelectric element, is significantly greater than the “deformation” component of the electric field caused by the “direct piezoelectric effect” from the influence of the essentially non-uniform deformation that appear and initially unknown fields in the piezoelectric element. Note that the non-uniformity of the deformation fields in the volume of the piezoelectric element is caused by many factors, in particular, the shape and location of the electrodes on the surfaces of the piezoelectric element, the characteristics of the control
electrical voltage on the electrodes and the attachment of the piezoelectric element to the surface of the structure [11, 12].

The formulation of a coupled boundary problem of electroelasticity for a structurally inhomogeneous body with an outer boundary, in particular, for a fragment of an elastic composite structure with a piezo-actuator fixed on the surface in the form of a composite plate with piezoelectric and piezopassive phases and electrodes consists of several equilibrium equations

\[ \sigma_{ij,r}(r) = 0, \]  
continuity equation

\[ D_{i,j}(r) = 0, \]  
equilibrium equation of defining relations

\[ \sigma_{ij}(r) = C_{ijmn}(r)\varepsilon_{mn}(r) - e_{nij}(r)\hat{E}_n(r), \]  
equilibrium equation for Cauchy relations of small elastic deformations

\[ e_{ij}(r) = \frac{[u_{i,j}(r) + u_{j,i}(r)]}{2}, \]  
equilibrium equation for coupling the stress

\[ \hat{E}_i(r) = -\phi_i(r), \]  
with the field of electric field potentials \( \phi(r) \) and boundary conditions, for example, in the form of given non-zero values of electric potentials on the electrodes of the piezo-actuator, mechanical fixation conditions (for displacement vector) or loading (for voltage vector) and, in addition, potentials or inductions (normal components to the border areas a) electric field for all parts of the outer boundary \( \Gamma \) of the area \( V \) with the fulfillment of the conditions of ideal contact on the interphase surfaces of continuity of the vectors of displacements, voltages and inductions the electric field in the area \( V \) where \( \sigma(r), \varepsilon(r) \) and \( u(r) \) are the fields of stresses, strains and displacements. \( \hat{D}(r), \hat{E}(r), \phi(r) \) are the fields of inductions, strengths and potentials of the electric field. As a result, the statement of the coupled boundary value problem of electroelasticity in the area \( V \) with an external boundary \( \Gamma \) will take the form:

\[ [C_{ijmn}(r)u_{m,n}(r)]_j + [e_{nij}(r)\phi_{,n}(r)]_j = 0 \]

\[ [e_{ijmn}(r)u_{m,n}(r)]_j - [\lambda_{j,n}(r)\phi_{,n}(r)]_j = 0 \]

for finding the displacement fields \( u(r) \) and electric field potentials \( \phi(r) \) taking into account the given boundary conditions, the continuity conditions of the electroelastic fields at the internal interphase boundaries and the conditions for loading the area \( V \) with an electric voltage between the actuator electrodes.

For the case of the composite areas \( V_{1,2} \) of the structure fragment and the piezo-actuator in the area \( V \) with the corresponding homogeneous regions with effective, in general, anisotropic electroelastic properties, we have

\[
\begin{bmatrix}
C(r) \\
e(r) \\
\lambda(r)
\end{bmatrix} = \sum_{f=1}^{2} \begin{bmatrix}
C^*_f \\
e^*_f \\
\lambda^*_f
\end{bmatrix} i_f(r), \quad i_f(r) = \begin{cases} 
1, & r \in V_f \\
0, & r \not\in V_f 
\end{cases}
\]

for the coefficients of differential operators (6), where the indicator functions \( i_{1,2}(r) \) for the areas \( V_1 \) of the actuator and the fragment of the structure \( V_2 = V \setminus V_1 \), the tensors of the effective elastic \( C^*_{1,2} \), piezoelectric \( e^*_{1,2} \) (in particular \( e^*_{1,2} = 0 \)) and dielectric \( \lambda^*_{1,2} \) properties of the areas \( V_{1,2} \) [12].
The use of "thermo-piezoelectric analogy" (2), (3) allows you to move from the system of differential equations (6) to a simpler

$$[C_{ijmn}^{*}(r)u_{m,n}(r)]_{j} - \beta_{ij}^{*}(r)\Delta T = 0,$$

where the field of temperature coefficients

$$\beta_{ij}^{*}(r) = \begin{cases} \epsilon(1)_{nij}(r)\zeta(1)_{n}(r), & r \in V_{1} \\ 0, & r \notin V_{1} \end{cases}$$

(9)

calculated through a known field $\zeta(r)$ with components

$$\zeta(1)_{n}(r) = E(1)_{n}(r)/U_{yp},$$

(10)

identifying the magnitude of the control voltage $U_{cont}$ on the electrodes of the piezoelectric element with the reduced heating temperature $\Delta T = U_{cont}$. Note that in some approximation, the inhomogeneous field $\zeta_{n}(r)$ in the area $V_{1}$ can be calculated on the basis of solving a model boundary value problem of electroelasticity for an unrelated piezo-actuator design. While the tensor of the coefficients of the linear thermal expansion is determined by the following ratio:

$$\alpha^{*}(r) = \begin{cases} \alpha(1)_{n}(r), & r \in V_{1} \\ 0, & r \notin V_{1} \end{cases}$$

(11)

where the components $\alpha(1)_{ij} = C_{(1)jmn}^{*}e^{*}(1)_{pnmn}(r)\zeta(1)_{p}(r)$ are calculated through the known tensors of the effective elastic $C^{*}$ and piezoelectric $e^{*}$ properties of the actuator and the field of coefficients $\zeta_{i}(r)$ that take into account the peculiarities of the geometric shape and arrangement of the electrodes of the piezo actuator.

When implementing the connection $\Delta T = \Delta U$ in the framework of the PC finite element analysis, you can use the simplified relation of the following form:

$$\alpha_{3i} = \frac{d_{3i}}{\Delta e_{i}} (i = 1,2,3),$$

(12)

where $\Delta e_{i}$ is the effective distance between the electrodes, the piezoelectric strain factor $d_{3i}$ characterizes the electromechanical properties of the piezoelectric material and describes the deformation of the material depending on the orientation of the electric field. The first index indicates the direction of the electric field, and the second index indicates the direction of deformation.

Knowing the values of the three piezoelectric strain coefficients $d_{31}, d_{32}$ and $d_{33}$ is enough to fully characterize the electromechanical properties of the piezoelectric material.

3. Results of the numerical simulation

According to the results of numerical simulation, stress and displacement fields (Figure 3, 4) were obtained for the sample made of unidirectional and equal strength fiberglass.

Analysis of the axial displacement fields $U_{y}$ revealed that when using an equal strength glass prepreg, the torsion angle of the sample is 0.187 °, and when using a unidirectional the torsion angle is 0.180 °. A comparative analysis of the results obtained revealed that when using equal strength prepreg, there is an increase in the torsion angle by 3.9% with the same value of the control voltages.
Figure 3. The normal movements $U_z$ distribution fields at the 1000V control voltage: a - equal strength glass prepreg sample; b – sample made from unidirectional glass prepreg.

Analysis of the $U_x$ axial movement fields revealed that when using an equal strength glass prepreg, the normal $U_x$ movements of $U_x$ are 0.833, and when using a unidirectional glass prepreg, the normal $U_x$ movements are 0.754. A comparative analysis of the obtained results revealed that when using an equal strength prepreg, an increase in the maximum axial bending movements $U_x$ by 10.39% occurs.

Figure 4. The normal movements $U_z$ distribution fields at the 1000V control voltage: a - equal strength glass prepreg sample; b – sample made from unidirectional glass prepreg.

According to the results of the research, we can formulate the following recommendations: when designing controlled PCM structures working for torsion, the maximum twisting effect of the structure is achieved when using equal strength materials. However, it is worth noting that when using equal strength fiberglass there is a decrease in the longitudinal flexural rigidity of the structure by 10%. When designing similar SMART structures, the reinforcement scheme and blade covering material must be selected on the basis of strength and stiffness requirements, taking into account the actual operational loads.

4. Conclusions

Thus, according to the results of the research, a mathematical model has been developed for calculating the stress-strain state of a sample equipped with control piezoactuators. The model implements the principle of thermo-piezoelectric analogy, which allows moving from the coupled boundary problem of electroelasticity to the boundary problem of thermoelasticity. A study of the convergence of finite element models of the sample was carried out. The simulation of the mechanical behavior of the sample, equipped with piezoactuators was conducted. It was revealed that using an equal strength material a greater torsion angle is achieved as compared to a unidirectional material. The difference in torsion angles was 3.9%.
Acknowledgments
The research was carried out at Perm National Research Polytechnic University with the support of the Russian Science Foundation (project № 18-19-00722).

References
[1] Kovalovs A, Barkanov E and Gluhihs S 2007 Journal of Physics: Conference Series 93(1) 3-9
[2] Brudanov A M 2015 Young Scientist 104(24) 101 - 104
[3] Chen P and Chopra I 1996 Smart Mate. Struct. 5(1) 35-48
[4] Cesnik C E S and Shin S J 2001 Smart Mater. Struct. 10(1) 53—61
[5] Cesnik C E S and Shin S J 2001 J. Solids Struct. 38(10) 1765-89
[6] Chattopadhyay A, Lin Q and Gu H 2000 AIAA J. 38(7) 1125-31
[7] Chattopadhyay A, Lin Q and Gu H 1999 Composites: Pt B, Eng. 30(6) 603-12
[8] Sekula M K, Wilbur M L and Yeager W T 1998 Proc. Amer. Helicopter Soc. 4th Decennial Specialist Conf. Aeromech. p 12
[9] Sekula M K, Wilbur M L and Yeager W T 2005 Proc. 61st Annual Forum Am. Helicopter Soc. p 14
[10] Wilbur M L and Sekula M K 2005 Proc. 61st Annual Forum Am. Helicopter Soc. p 14
[11] Makarova I S 2012 Vestn. sam.gos tech. un-that. Ser. Phys.-mat. Science 3(28) 191-195
[12] Pan’kov A A 2009 Statistical mechanics of piezocomposites (Perm: Publishing house of the Perm state technical university) p 480
[13] Kovalev A, Barkanov E, Ruchevsky S and Wesolovsky M 2017 Mechanics of composite materials 53(2) 1-20
[14] Grinev M A, Anoshkin A N, Pisarev P V, Zuiko V Yu and Shipunov G S 2015 PNRPU Mechanics Bulletin 3 38-51