Research of the Piezo Actuator Location Influence on the Twist Angle of a Model Helicopter Blade Made of Polymer Composite Materials

To cite this article: E Barkanov *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **511** 012029

Research of the Piezo Actuator Location Influence on the Twist Angle of a Model Helicopter Blade Made of Polymer Composite Materials

E Barkanov[1], A N Anoshkin[2], P V Pisarev[2] and V A Ashihmin[2]

[1]Institute of Materials and Structures, Riga Technical University, Riga, Latvia
[2]Perm National Research Polytechnic University, Perm, Russia

E-mail: pisarev85@live.ru

Abstract. The article formulates a mathematical model for calculating the stress-strain state (SSS) of a model helicopter blade equipped with piezo actuators. In determining the twist angle of the model blade, the principle of thermo-piezoelectric analogy was used, which allowed moving from the related boundary problem of electro elasticity to the boundary problem of thermo elasticity. A comparison was made of the deformation fields for model blades with various arrangement of piezo actuators and different materials of the spar. We analyzed the convergence of the finite element model of the blade. The limiting twist angles of the model blade were determined in the range of the control voltages operating values applied to the piezo actuators. Recommendations for the placement of piezo actuators on a model helicopter blade were formulated.

1. Introduction

Currently, among all types of aircrafts, helicopters are the ones most exposed to vibration. The helicopter rotor's characteristics worsen with increasing airspeed due to the effect of compressibility of air, the appearance of a stall on the retreating blades, an increase in the loads applied to the blades control system and an increase in vibration and noise levels [1, 2].

Many works [3–8] are devoted to the problem of numerical simulation of active control systems; most of them are based on simple two-dimensional models that apply combinations of numerical simulations for longitudinal and transverse analysis of the stress-strain state (SSS) along the blade length. These simplified models are used to estimate the distribution of stiffness and mass of the blade with variable geometry. One of the first models of a thin-walled laminated profile equipped with active controls was described in [3]. In this paper, the task was set on the basis of the classical theory of shells, the model was verified. Other models appeared later, describing the dynamic behavior of rotating solid blades with embedded piezoelectric elements. These models are taking into account the anisotropy of properties, as well as centrifugal and Coriolis inertia force [4]. However, the rotor blade of the helicopter is a very flexible structure, and therefore a blade numerical simulation model should consider non-linear deformations of flexible structures, including the contact with the control elements [5-6]. Mathematical models for calculating the mechanical characteristics and electro elastic fields in piezoelectric composite materials with different arrangement of control piezo elements are presented in [7-10].

The tasks of multiparameter optimization of the composite structure based on integral models (in unrelated formulation) were solved in the works [11–14], in these works the parameters of active (control) and power elements were determined.

Overall, it can be concluded that the approaches used today for the numerical simulation of SMART structures are largely based on simplified models and integral methods of calculation. These approaches determine a narrow range of parameters with which the performance characteristics of SMART structures can be adjusted. These models have almost exhausted their capabilities. In turn, the capabilities of modern computing, numerical methods and the corresponding development of the experimental base makes it possible to make a new qualitative leap in the design and creation of SMART structures with optimal characteristics, which in turn will allow achieving the maximum reduction of noise and vibrations of aircrafts.

To successfully solve the problems of reducing vibration in aircrafts using piezo actuators, it is necessary to determine the constructional features of the control elements, as well as their locations. It is important to develop new mathematical models for calculating the SSS of piezoelectric layered polymer composite materials (PCM), equipped with piezo actuators.

For this work, a numerical research has been carried out to determine the influence of the location of piezo-actuators on the twist angle of a model blade made of PCM with different material of the spar. Three types of arrangement of piezo actuators on the blade were considered: lower, upper, and combined arrangement.

2. Numerical model

To conduct a numerical research of the piezo actuators location influence on the twist angle, a three-dimensional geometric model of a helicopter blade was developed. The NACA 23012 profile was used as an aerodynamic profile. The researches blade profile has the following geometrical characteristics: length — 4528 mm, chord length — 310 mm. The general view and dimensions of the model blade profile are shown in Figure 1. This profile has a C-shaped spar made of aluminum, fiberglass skin (GFRP), MFC actuators embedded in the skin, foam aggregate (Rohancell 51FX) and balance weight (lead) [15].

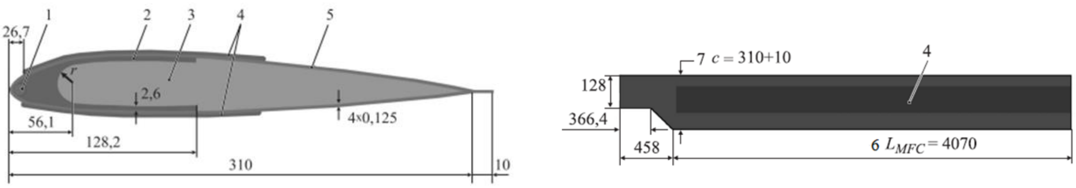

Figure 1. Cross-section and shape of a full-scale rotor blade. 1 - the balancing load; 2 –the spar; 3 –the foamed aggregate; 4 –the MFC actuator; 5 –the skin; 6 - the center of rotation; 7— the chord of the blade c = 310 + 10; 8 –the length of the MFCL MFC actuators= 4070; 9 - the radius of the rotor Rr = 4900. The dimensions are in millimeters [16]

The researched helicopter blade was made of textile fiber reinforced plastic with reinforcement scheme [0°/90°]. Technical elastic constants of fiberglass were calculated using ANSYS PC and comprised $E_x = E_y = 18.25$ GPa, $E_z = 6.05$ GPa, $\nu_{xy} = 0.148$, $\nu_{yz} = \nu_{xz} = 0.299$, $G_{xy} = 4$ GPa, $G_{yz} = G_{xz} = 3$ GPa. Technical elastic constants of the blades and actuator materials are taken from [4] MFC – $E_x = 30$ GPa, $E_y = E_z = 15.5$ GPa, $\nu_{xy} = 0.35$, $\nu_{yz} = \nu_{xz} = 0.4$, $G_{xy} = 5.7$ GPa, $G_{yz} = G_{xz} = 10.7$ GPa, $d_{31} = d_{32} = -1.98{*}10^{-10}$ м/В, $d_{33} = 4.18{*}10^{-10}$ MW; Rohancell 51FX – E = 13.79 MPa, G = 14 MPa, ν = 0.25; Pb – E = 13.79 GPa, G = 2 GPa, ν = 0.44.

For the numerical research the following boundary conditions (BC) were formulated: from the end of the structure attached to the rotor, homogeneous BCs of the second kind were specified. For piezoactive elements, the given heating temperature was set, equivalent to the control voltage $\Delta\hat{T} =$

U_{cont}. In addition, a volume force was applied to the blade – gravitation force. A complete adhesion was set in the area of the layers' and the construction structural elements' junction.

For better convergence of the solution and reduction of the errors of the results obtained, a computational grid was generated, the cells of which have a prismatic shape. Local adaptation was carried out in the areas of high stress gradients, namely in the area of the spar, the size of the adaptation element was 1 mm. The maximum element size was 5 mm, the minimum - $8*10^{-3}$ mm, for each material layer, the total number of design elements was 1.1 million. In addition, the construction and local grinding of the mesh did not allow sharp differences in the geometric dimensions of adjacent elements.

In the framework of the numerical experiments, the mechanical behavior of the model blade equipped with piezo actuators was simulated at a control voltage level of 1000V. The plan of the numerical experiments is presented in table 1.

Table 1. Plan of the numerical experiments for the model blade

Number of the numerical experiment	Reinforcement scheme	Piezo actuator arrangement	The voltage applied, V (^{0}C)
1	[0°/90°]	Upper	1000
2	[0°/90°]	Lower	1000
3	[0°/90°]	Combined	1000

To describe the inverse piezoelectric effect in the framework of the developed mathematical model, it is proposed to use the thermo-piezoelectric analogy between the piezoelectric and thermo-induced deformations. The analogy allows us to move from the need to solve a related boundary problem of electro elasticity to the solution of a much simpler unbound boundary value problem of thermo elasticity. The analogy is based on the hypothesis of the electric non-uniform field invariance in the piezoelectric element (electric field arising from the control voltage on its electrodes) to the 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 is fixed, piezo actuator. Therefore 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_{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 effects of the essentially inhomogeneous deformation fields appearing and initially unknown in the piezoelectric element. Note that the heterogeneity 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 voltage on the electrodes and the attachment of the piezoelectric element to the surface of the structure [17, 18].

The tensor of reduced coefficients of linear thermal expansion is determined by the relation:

$$\alpha_{3i} = \frac{d_{3i}}{\Delta_{el}} (i = 1,2,3), \tag{1}$$

where Δ_{el} 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.

The values of the three coefficients of the piezoelectric deformations d_{31}, d_{32}, and d_{33} are enough to fully characterize the electromechanical properties of the piezoelectric material.

3. Results of the numerical simulation

According to the results of the numerical simulation of the model blade mechanical behavior, stress fields and axial displacements were obtained (Figure 2).

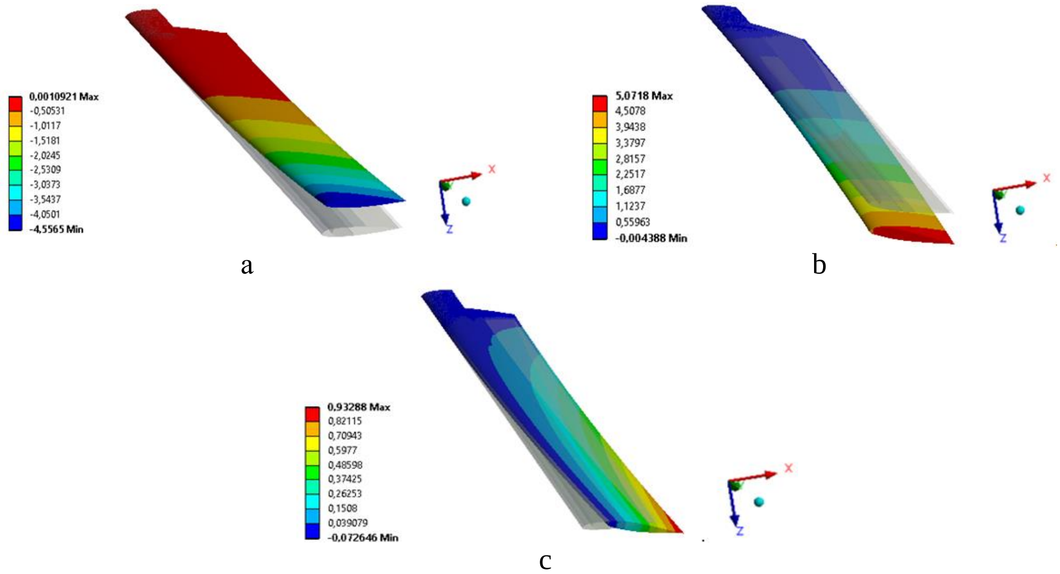

Figure 2. Fields of distribution of axial displacements U_z with the value of the control voltage 1000 V a - upper; b - lower; c - combined

Table 2 presents the results of the numerical simulation for a blade equipped with piezo actuators.

Table 2. Results of the blade numerical simulation

Reinforcement scheme	Spar material	Piezo actuator arrangement	U_x, mm	U_y, mm	U_z, mm
[0°/90°]	GFRP	Combined	1.79	0.304	1.4831

Analysis of the results of the model blade SSS numerical simulation showed that with the upper and lower placement of the torsional piezo actuator on the profile of the model blade, mutual compensation of opposing bending moments occurs, along with the predominance of torque and, as a result, twisting deformations. When designing rotor blades with variable geometry, it is recommended to place piezo actuators on both sides of the construction profile. The maximum value of the twist angle of the model blade at a control voltage level of 1000 V, with a combined (upper and lower) arrangement of the piezo actuator was φ=3.1°.

4. Verification of the numerical model

As part of the developed mathematical models' verification, a comparison was made of the results of the numerical research (performed using ANSYS software) with the results of laboratory tests of model layered PCM samples, equipped with bending piezo actuators, mechanical behavior. Figure 3 shows a general view of the samples and the experimental laboratory setup.

IOP Conf. Series: Materials Science and Engineering **511** (2019) 012029 doi:10.1088/1757-899X/511/1/012029

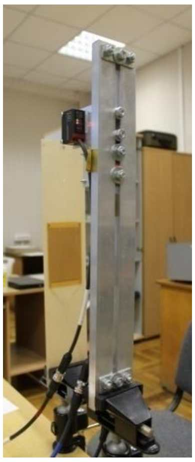

Figure 3. General view of the sample and the experimental laboratory setup

For numerical simulation, three-dimensional models of the samples were constructed, corresponding to the real ones. The samples consisted of four anisotropic layers of fiberglass on the basis of T13 glass fabric, made by the infusion method. The geometrical characteristics of the samples are 400x45x1.1, selected on the basis of the size of the M8557-F1 torsional piezo actuators used.

Comparison of the numerical research results with the results of laboratory tests was carried out at the twist angle of the free end. The twist angle was determined by the formula:

$$\sin\alpha = \frac{a}{c}, \tag{2}$$

where α is the twist angle; a - adjacent leg; c - hypotenuse.

The numerical simulation and the laboratory experiment were carried out with a control voltage of 25-125V

The following displacement fields were obtained from the results of numerical simulation of torsion tests for a fiberglass sample (Figure 4):

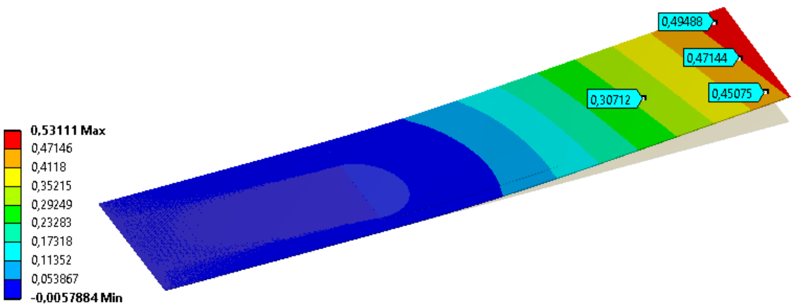

Figure 4. U_z displacement fields on the sample equipped with a torsional piezo actuator

Analysis of the obtained fields of displacements along the Z axis showed that the maximum twist angle occurs at the free end of the sample and equals 24', which correlates well with the experimental values.

Based on the results obtained, a graph of the sample's twist angle dependence on the control voltage applied to the piezo actuator was constructed (Figure 5).

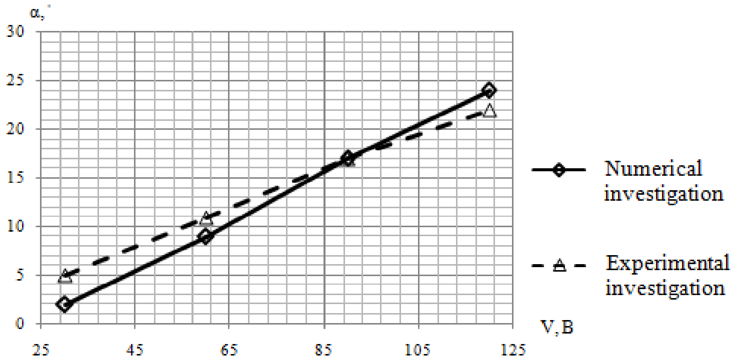

Figure 5. Graph of the dependence of the twist angle of the free end of the sample on the control voltage applied to the piezo actuator

The analysis of dependencies revealed that the results of numerical simulation are within the range of the results of torsion tests. The error in comparison with the results obtained for torsion tests does not exceed 10%.

5. Conclusion

Thus, according to the results of numerical researches, a new mathematical model of a helicopter blade, equipped with control piezo actuators, was developed. Research of the convergence of the finite element model of the blade has been carried out. The simulation of the mechanical behavior of the blade, equipped with piezo actuators, was carried out with the applied control voltage 1000V. Analysis of the axial displacement fields U_z showed that the two-way arrangement of piezo actuators in torsion is most effective. The limiting twist angles of the model blade were determined in the range of the control voltages operating values applied to the piezo actuators.

Acknowledgments

The reported study was partially supported by the Government Perm Krai, research project No. C-26/797 dated 12/21/2017.

References

[1] Animits V A, Borisov E A, Kritsky B S and Mirgazov R M 2016 *Trudy MAI* **85** 1-25
[2] Kritsky B S, Mirgazov R M and Le V Ch 2016 *Scientific Herald of MSTU GA* **19** **6** 68-76
[3] Chattopadhyay A, Liu Q and Gu H 1999 *Composite Part B: Engineering* **30** **6** 603 – 612
[4] Cesnik C E S and Shin S J 2001 *Smart Materials and Structures* **10** **1** 53 – 61
[5] Büter A and Breitbach E 2000 *Aerospace Science and Technology* **4** **5** 309–319
[6] Ghiringhelli G L, Masarati P and Mantegazza P 2001 *Composite Structures* **52** **1** 113–122
[7] Park J S and Shin S J 2007 *ICCES* **4** **4** 265–269
[8] Sekula M K, Wilbur M L and Yeager W T 2005 *Proc. of the 61st Int. Annual Forum of the American Helicopter Society* (Grapevine, USA) p 14
[9] Cesnik C E S, Mok J, Parekh A and Shin S 2004 *Proc. of the 45th AIAA/ASME/ASCE/ASC Structures* (Palm Springs, USA) p 10
[10] Cesnik C E S, Mok J, Morillo J A and Parikh A S 2004 *Proc. of the 30th European Rotorcraft*

IOP Conf. Series: Materials Science and Engineering **511** (2019) 012029 doi:10.1088/1757-899X/511/1/012029

Forum (Marseille, France) p 14
[11] Shin S, Cesnik C E S, Wilkie W K and Wilbur M L 2008 *Journal of Intelligent Material Systems and Structures* **19 12** 1443-56
[12] Park J S, Shin S J and Kim D K 2008 *International Journal Aeronautical and Space Sciences* **9 2** 18–33
[13] Sekula M K and Wilbur M L 2014 *NASA Technical Reports Server (NTRS)* p 13
[14] Barkanov E, Gluhih S and Kovalov A 2008 *Mechanics of Advanced Materials and Structures* **15 3-4** 325-334
[15] Airfoil database list [Electronic resource] URL: http://airfoiltools.com/search/airfoils?m=a
[16] Kovalev A, Barkanov E, Ruchevsky S and Vseolovski M 2017 *Mechanics of composite materials* **53 2** 1-20
[17] Makarova I S 2012 *Herald of the Samara State Technical University. Series of Physics and Mathematics* **3 28** 191-195
[18] Pan'kov A A 2009 *Statistical mechanics of piezocomposites* (Perm: Publishing house of Perm State Technical University) p 480