Numerical model of optical fiber piezoelectric feedback detector used for aviation composite constructions elements’ geometry control

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Abstract. The authors developed a numerical 3D model of a piezoelectroluminescent fiber-optic sensor for diagnosing a volumetric stress-strain state in a helicopter blade with controlled geometry. The authors of the article have performed a numerical calculation of non-uniform coupled electro-elastic fields in the elements of a sensor fragment embedded in a fiberglass sheathing of the main helicopter propeller. The calculation was carried out taking into account the action of the control voltage on the sensor electrodes. The numerical values of the informative and control coefficients of the sensor necessary for diagnosing the components of the strain tensors at the macro and micro levels of the textile composite are calculated.

1. Introduction
High-loaded elements of aircraft structures, such as an airplane wing or helicopter blades, create significant oscillations and noise due to changes in the aerodynamic loads acting on them when their azimuthal angle changes. With the advent of piezo-active materials, it became possible to develop efficient intelligent systems to tackle vibrations. Piezoactuators, integrated into the wing skin or rotor blades, create dynamic twisting and curvature of the structure, adapting it at any time to the flight conditions, which significantly reduces vibrations, noise and, in general, improves the flight characteristics of the structure.

Modern high-precision sensors based on intelligent materials are needed to monitor structural deformation fields and provide feedback in the controlled elements of composite structures. Such sensors can be integrated into complex composite structures as sensitive, translational and control elements that adapt to given conditions. For these purposes, fiber optic sensors are widely used, in which fiber is the main element. Optical fiber can be used as a transmission line of an informative signal and/or a sensitive element, in particular, in the form of a section of an optical fiber with a Bragg diffraction grating [1–4]. A promising solution to the problem of feedback in the elements of composite structures are piezoelectric sensor networks [5–8], embedded in the structure. New designs of piezoelectroluminescent fiber-optic sensors for diagnosing pressure [9], complex volumetric stress-strain state [10] and temperature [11] inside the composite structure were proposed in the patents [9–11]. These designs implement the algorithms [12, 13] of the receiver-analyzer processing integrated optical signals at the output of the sensor optical fiber.

The goal of this work is to develop a numerical model in ANSYS and to study the patterns of distribution of bounded electroelastic fields in the elements of a piezoelectric-luminous optical
fibersensor [10] embedded inside a representative element of a deformable composite structure with its complex volumetric stress-strain state.

2. Model of the sensor
Piezoelectroluminescent fiber-optic sensors [9-12] are intended for the specified diagnosis of pressure distribution [6, 12] and/or temperature [11] and complex volume stress-strain state $\sigma^*$ inside composite structures (Figure 1) [8] based on the results of processing a receiver-analyzer of the intensities $I$ of the integrated light signals at the output from the sensor fiber. The sensor (Figure 1) is an optical fiber 1 with coaxial electroluminescent 2 and piezoelectric 3 layers.

![Figure 1. Piezoelectroluminescent fiber-optic sensor of the volumetric stress state (a), computational domain with a sensor fragment (b), test points in the cross section of the sensor (c)](image)

Optical fiber and electroluminescent layer are separated by an internal translucent or perforated control electrode 4, an external control electrode 5 is located on the surface of the piezoelectric layer. The buffer layer 6 is required for mechanical translation of the sensor piezoelectric elements of a homogeneous macroscopic (averaged) component of the micro-inhomogeneous stress-strain state from the loaded composite region 7 in order to eliminate the “parasitic” effect of random pulsation fields of the microstructure in the region 7 of the sensor vicinity to the measurement results. In the sensor (Figure 1), the electroluminescent and piezoelectric layers are divided into geometrically equal radial-longitudinal boundaries shared by both layers. In particular, for six-parameter sensors, six “measuring elements” are distinguished - cylindrical two-layer sectors. In the sensor’s measuring elements directions of the piezoelectric phases (piezoelectric elements) spatial polarizations and the frequency of the light output electroluminescent phases are different in all six sectors. The polarization directions of the piezoelectric elements are determined from the condition of non-coplanarity of the polarization directions for arbitrary three sensor sectors. Piezoelectric elements can be either different or same piezoelectric, in particular, PVDF polymer transversely isotropic material, but with different spatial polarization directions by sector. The direction of polarization is the axis of symmetry of the PVDF piezoelectric. Informative light signals occur in the local areas of the measuring elements of the sensor due to the mechanoluminescent effect (due to the interaction of the piezoelectric 3 and electroluminescent 2 sensor elements), penetrate the optical fiber 1 through the translucent electrode 4 and are transmitted via optical fiber 1 to the receiver-analyzer. The control voltage $U_{cont}$ on the electrodes 4, 5 makes it possible to identify the inhomogeneities locations of the diagnosed characteristics, in particular, the deformation fields in composite structures, using scanning algorithms [12].
The sensor (Figure 1) is characterized by its control and informative transfer coefficients, which establish a linear relationship between the electrical voltages on the electroluminescent layer

\[ U_{\text{lum}(j)} = \alpha_{1(j)} U_{\text{cont}} + \alpha_{2(j)mn} \varepsilon_{mn} \]  

(on each of the six elements of the electroluminescent layer \( U_{\text{lum}(j)} \) in the \( j \)-th circular sector) with the amount of control voltage \( U_{\text{cont}} \) applied to the electrodes and diagnosed parameters \( \varepsilon^* = \{ \varepsilon_{11}^*, \varepsilon_{22}^*, \varepsilon_{33}^*, \gamma_{23}^*, \gamma_{13}^*, \gamma_{12}^* \} \) in the cross section of the sensor with coordinates, where the desired axial \( \varepsilon_{11}^*, \varepsilon_{22}^*, \varepsilon_{33}^* \) and shear deformation \( \gamma_{23}^*, \gamma_{13}^*, \gamma_{12}^* \) of the diagnosed complex volume deformed states are calculated in the considered location inside the composite structure, \( j = 1.6 \).

Figure 2 schematically depicts a helicopter blade [14] with a bimorph piezo-actuator of flexural type 8 located inside the rear part of the blade profile, supplemented with a fiber-optic sensor 9 with spiral stacking inside the near-surface (in particular, local) area of the skin with controlled geometry. Feedback is necessary to adapt the operating mode of the piezo-actuator (for example, the magnitude and location of the controlled force effect of the piezo-actuator on the actuator and the blade profile) to the special aspects (including random weather conditions) of the structure’s service.

3. Numerical simulation

Geometrical parameters of the numerical model of the sensor (Figure 1): radii of concentric cylindrical surfaces \( r_1 = 1 \) mm, \( r_2 = 1.2 \) mm, \( r_3 = 1.4 \) mm, \( r_4 = 2.8 \) mm directed along the axis in the center of the parallelepiped with edges oriented along the coordinate axes \( r \) and with values of 16.8 mm in the \( r_1 \) and 27.2 mm in the \( r_3 \) axis; the computational domain was discretized into \( 18 \times 10^6 \) finite elements, of which \( 12 \times 10^6 \) stand for the cylindrical region of the sensor itself, taking into account the buffer layer. Electroelastic characteristics of the sensor phases: the isotropic properties of the fiber, the isotropic properties of the polymer electroluminescent phosphor, the transversely isotropic properties of the PVDF polymer piezoelectric (in the main axes) are given in [15], the isotropic elastic properties of the polyethylene buffer layer in [16], the transversely isotropic with a symmetry axis parallel to the parallelepiped properties are equal to the effective properties of a unidirectional fiberglass plastic with a 0.6 volume fraction of fibers.

To calculate the informative coefficients \( a_{(ij)} \), simple deformations \( \varepsilon_{ij}^* \) of the parallelepiped were sequentially set through the displacements \( \hat{u}_i = \varepsilon_{ij}^* \hat{r}_j \) of points \( \hat{r} \) on its faces for given zero values of the control potential of the sensor electrodes. To calculate the control coefficients \( a_{(ij)} \), we considered the case of the effect of a unit voltage \( U_{\text{cont}} \) on the control electrodes in the absence of displacements for the points of the parallelepiped, \( \varepsilon^* = 0 \). According to the results of numerical simulations, numerical values of the informative \( a_{(ij)} \) and \( a_{(ij)} \) control coefficients of the sensor (Figure 2) are needed to diagnose a complex volumetric stress state inside composite structures, the find locations and inhomogeneity
values of the components of stress and strain tensors at macro and micro levels of the composite diagnostic algorithms [12].

Figure 3. Electric potentials in the indicator sectors of the sensor for the given control voltage $\hat{U}_{\text{cont}} = -1$ V ($\varepsilon^\ast = 0$) (a), electric potentials for the axial deformations $\varepsilon_{11}^\ast$ (b), $\varepsilon_{22}^\ast$ (c), $\varepsilon_{33}^\ast$ (d) equalling to $10^{-5}$, electric potentials for the shear angles $\gamma_{23}^\ast$ (e), $\gamma_{13}^\ast$ (f) equalling to $0.6176 \cdot 10^{-5}$, $\gamma_{12}^\ast = 10^{-5}$ (g) electric potentials in the indicator sectors of the sensor for zero control voltage ($\hat{U}_{\text{cont}} = 0$ V)
Thus, when solving the problem of diagnosing a stress-strain state in composite structures, the desired components of the macrodeformation tensor $\varepsilon^*$ of the composite are determined from the solution of a system of linear algebraic equations

$$
\begin{bmatrix}
\varepsilon_{11}^* \\
\varepsilon_{22}^* \\
\varepsilon_{33}^* \\
\gamma_{12}^* \\
\gamma_{13}^* \\
\gamma_{23}^*
\end{bmatrix} = \begin{bmatrix} \Delta \end{bmatrix}
$$

(2)

found using algorithms [12] (for processing the intensities of optical signals at the output of the sensor optical fiber with varying control voltage $\hat{U}_{cont}$) components $\Delta_{ij}$, taking into account the control coefficients of the sensor $a_{i,j}(1)$.

4. Conclusion

A numerical 3D model of a piezoelectroluminescent fiber optic sensor has been developed for diagnosing the volumetric stress-strain state in a helicopter blade with controlled geometry. A numerical calculation of non-uniform coupled electro-elastic fields in the sensor fragment elements embedded in the fiberglass sheathing of the helicopter rotor is performed, taking into account the effect of the control voltage on the sensor electrodes. The numerical values of the informative and control coefficients of the sensor necessary for diagnosing the components of the strain tensors at the macro and micro levels of the textile composite are calculated.

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