Diagnostics of gradient strains field in polymer composite material with built-in fiber optic piezosensor

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Abstract. Description of design, principles and functioning of distributed optical fiber piezoelectroluminescent (PEL) sensors embedded in polymer composite structures for refined monitoring of inhomogeneous "gradient" strains fields inside structures is given. The informative light signal occurs due to the mechanical-luminescent effect caused by the interaction of the piezoelectric and electroluminescent elements (sectors of layers) of the sensor. Monitoring are found as a result of digital processing of the information spectrum of the intensities of the integral light signal at the output from the optical fiber taking into account the known dependences of the light output intensity of the each j-th electroluminophore on electrical voltage applied thereto. Mathematical models have been developed, settings and problem solving scheme on finding numerical values of transfer information and control coefficients of PEL sensors are given, and results of numerical calculation of transfer coefficients of sensor for case of small values of gradients of diagnosing strains field are presented.

1. Introduction

To monitor the structural strains fields and to diagnose the occurrence and development of defects in elements of composite structures, modern high-precision sensors based on intelligent materials are required as sensitive, controlling and adaptable to given conditions of diagnostics of elements for integration into composite structures. For these purposes, fiber optic sensors are widely used, in which the optical fiber is used as a transmission line for an information signal and/or a sensitive element, in particular, with a diffraction Bragg grating. A promising solution to the problem of diagnosing inhomogeneous strains fields and the presence of defects in the elements of composite structures is sensory piezoelectric networks [1-3] embedded in the structure of the structure. "Mechanical-luminescent effect" is the light output during mechanical exposure is observed both in crystal phosphors and in composites with piezoelectric and electroluminescent phases. The luminescence of the electroluminophore in the composite was observed at values of electric voltage in the range from 2, ..., 5 V [4]. In [5], magnetic-luminescent effect for three-phase composite with magnetostRICTive, piezoelectric and electroluminescent phases for possible application in magnetic resonance imaging, optical control of magnetic fields is investigated. For visualization and monitoring of dynamic vibration load the mechanical-luminescent effect was used [6] in the structure of sensor - piezoelectric plate with external electrodes connected to electroluminescent layer on the plate end. Mathematical modeling of processes in piezoelectric sensor elements is carried out on the basis of solutions of boundary-value problems of electroelasticity theory by analytical [7-10], numerical [11-15] methods of continuous medium mechanics.
New designs of distributed piezoelectroluminescent (PEL) optical fiber sensors for refined diagnostics of temperature, pressure [18], volumetric stress-strain state [19] based on the results of digital processing of [18-20] integral optical signals at the output of the optical fiber of the sensor are described in [16, 17]. The informative light signal occurs due to the mechanical-luminescent effect caused by the interaction of the piezoelectric and electroluminescent layers of the sensor. The purpose is to develop a mathematical model, setting and a scheme for solving the problem of finding numerical values of transfer information and control coefficients of embedded PEL sensors [17] for refined monitoring of "gradient" inhomogeneous strains fields inside loaded polymer composite structures.

2. Setting the task

The solution of the problem of finding distribution of tensor values of "macrostrain" \( \varepsilon^* \) (this is the value of the averaged "micro" structural strains field) for a continuous, for example, along the coordinate axis \( r_3 \) of some local area inside unidirectional fibrous fiberglass (figure 1) is considered, in general, taking into account existing and considered "significant" values of gradients \( \nabla \varepsilon^* \) of the desired strains field \( \varepsilon^*(r_3) \) along the studied continuous area of the composite material. Here, the diagnosed continuous local area is the local neighborhood of the continuous fiber-optic PEL sensor [17], oriented along the axis \( r_3 \) and embedded in the composite material at the stage of its production to solve this problem. The sensor consists of an optical fiber with a continuous (uniform and continuous along the sensor axis) shell of "measuring elements" (it are two-layer electroluminophore/piezoelectric sectors) and an external uniform buffer layer; first electrode (translucent) is located on surface of optical fiber, and second electrode - on common external cylindrical surface of sectors of piezoelectric elements. For different sectors, piezoelectric elements are made of the same PVDF material, but with different (non-planar) polarization directions, while sector electroluminophores also have different "colors" of light output spectra (figure 1a); real colors in the red range. The resulting electrical voltage at the \( j \)-th electroluminescent element is \( U_{\text{lum}}(j) \), where \( j = 1, n \). The dependences of the light output intensity \( I_{\text{lum}}(j) \) of the electroluminophores on electrical voltage \( U_{\text{lum}}(j) \) applied thereto are also known. The number of "measuring elements" \( n \) is determined by the purpose of the sensor and the number of measured parameters, in particular for the "one-parameter case" we have an axisymmetric sensor of pressure or temperature [16, 18]. The diagnosable strain \( \varepsilon^* \) of the composite material lead to strain of the entire sensor (figure 1) and, in particular, each of its piezoelectric elements with the appearance of informative electric fields in them, the visualization of which takes place on the corresponding electroluminescent elements inside each "measuring element" of the sensor. The resulting informative light signals penetrate through the side surface of the optical fiber into and are recorded at the output of the optical fiber. Control voltage \( U_{\text{con}} \) is applied to electrodes to implement various diagnostic algorithms [18-20].

Figure 1. Cross-section of PEL sensor (a) and calculation area (b) of numerical model
3. Algorithm for calculating the transfer coefficients of the PEL sensor

Gradients \( \nabla \varepsilon^* \) of the field of strain \( \varepsilon^* \) to be diagnosed lead to the appearance of gradients along the coordinate \( r_3 \) of both strain and electric fields in the elements of the PEL sensor. As a result, the luminescence intensities of the local portions \( dr_3 \) of the electroluminescent elements of the sensor in the cross-section with the coordinate \( r_3 \) will depend both on the values of strains to be diagnosed \( \varepsilon^*(r_3) \) and on the values of gradients \( \partial \varepsilon^*/\partial r_3 \) in this cross-section. Therefore, to solve the problem, it is necessary to use a "gradient" sensor with 12 measuring PEL elements (figure 1), by means of which it is possible to find the value \( \varepsilon^* \) and gradient \( \partial \varepsilon^*/\partial r_3 \) for each independent component \( \varepsilon^*_i \) of the diagnosed strain tensor \( \varepsilon^* \) in each section with the sensor coordinate \( r_3 \) taking into account decomposition

\[
U_{\text{hom}(j)} = a_{U(j)} U_{\text{con}} + a_{\varepsilon(i)mn}^0 \varepsilon^*_{mn} + a_{\varepsilon(i)mn}^1 \frac{\partial \varepsilon^*_{mn}}{\partial r_3},
\]

where \( j = 1, 12 \). Note that additional consideration of the second derivatives \( \partial^2 \varepsilon^*/\partial r_3^2 \) becomes possible by increasing the number of measuring elements in the sensor to 18; in this case, an additional term \( a_{\varepsilon(i)mn}^2 \partial^2 \varepsilon^*_{mn}/\partial r_3^2 \) appears on the right side (1).

Transfer information \( a_{\varepsilon(i)}^0 \), \( a_{\varepsilon(i)}^1 \), and control \( a_{U(j)} \) coefficients of decomposition (1) have constant values and are characteristics of the sensor and are located experimentally or as a result of numerical simulation through calculated numerical values of electric potentials at control points (figure 1a) at the boundary of the electrolumino/piezoelectric in the middle cross section of the sensor fragment for various simple cases of loading. Thus, for calculating control coefficients \( a_{U(j)}(1) \), the case of acting on the control electrodes of a single electric voltage \( U_{\text{con}} \) in the absence of movements for the points of the parallelepiped faces (figure 1b), which corresponds to equalities, \( \varepsilon^* = 0, \partial \varepsilon^*/\partial r_3 = 0 \), is considered. For calculation of informative coefficients \( a_{\varepsilon(i)mn}^0 \) simple strains \( \varepsilon^*_{ij} \) of parallelepiped (figure 1b) are sequentially set through displacements \( \hat{u}_1 = \varepsilon^*_{ij}\hat{r}_i \) of points \( \hat{r} \) on its faces at given zero values \( U_{\text{con}} = 0 \) of control potentials on electrodes of sensor, \( \partial \varepsilon^*/\partial r_3 = 0 \). To calculate the informative "gradient" coefficients, \( a_{\varepsilon(i)mn}^1 \), the following displacements (were found using the Cesaro formulae) are sequentially set: first group is

\[
\begin{align*}
\hat{u}_1 &= k_1 \hat{r}_1, \quad \hat{u}_2 = 0, \quad \hat{u}_3 = -k_1 \hat{r}_1^2 / 2, \\
\hat{u}_1 &= 0, \quad \hat{u}_2 = k_2 \hat{r}_2, \quad \hat{u}_3 = -k_2 \hat{r}_2^2 / 2, \\
\hat{u}_1 &= 0, \quad \hat{u}_2 = 0, \quad \hat{u}_3 = k_3 \hat{r}_3^2 / 2, 
\end{align*}
\]

second group is

\[
\begin{align*}
\hat{u}_1 &= k_1 \hat{r}_1, \quad \hat{u}_2 = k_1 \hat{r}_1, \quad \hat{u}_3 = -k_1 \hat{r}_1, \\
\hat{u}_1 &= k_2 \hat{r}_2, \quad \hat{u}_2 = 0, \quad \hat{u}_3 = 0, \\
\hat{u}_1 &= 0, \quad \hat{u}_2 = k_3 \hat{r}_3, \quad \hat{u}_3 = 0
\end{align*}
\]

of points \( \hat{r} \) of parallelepiped faces for six different gradients \( k = \partial \varepsilon^*/\partial r_3 \) of axial (2) and shear (3) strains \( \varepsilon^*_{ij} \) of parallelepiped at equality \( \varepsilon^* = 0 \) in middle cross section \( (r_3 = 0) \) of sensor fragment (figure 1b) at specified zero values \( U_{\text{con}} = 0 \) of control potentials on sensor electrodes.

4. Results of numerical modeling

In the numerical simulation of the optical fiber PEL sensor (figure 1), the known \([19, 21]\) values of the electroelastic characteristics of the polymer electrolumino/piezoelectric PVDF (in the main axes), polyethylene (for the buffer layer) and the effective properties of unidirectional fibrous fiberglass with a volume fraction of fibers 0.6 were used. Numerical calculation of transfer information \( a_{\varepsilon(i)} \) and control \( a_{U(j)} \) coefficients of the sensor is carried out for a private mathematical model with six \( (j = 1, 6) \)
measuring PEL elements, when there are no (negligible values) gradients \( \forall \varepsilon^* \approx 0 \) of the desired distributed values of the strain tensor and decomposition (1) goes to a partial form

\[
U_{\text{lum}(j)} = a_U(j)U_{\text{con}} + a_{\varepsilon(j)mn} \varepsilon^*_{mn}.
\]

The diagnosable values of the strain tensor \( \varepsilon^* \) components in the local area of the composite material are found numerically from the solution of the system of linear algebraic equations

\[
[A] = \{\Delta\}, \quad [A] = \begin{bmatrix}
-1.1256 & 0.18152 & 0.48606 & 20.431 & -0.1758 & -0.4830 \\
-2.1181 & 10.627 & -2.6803 & 8.0761 & 3.7178 & 6.0422 \\
-13.098 & -6.6458 & 17.76 & 4.436 & -10.470 & -13.643 \\
-6.0193 & 3.6336 & 2.4845 & -0.749 & -21.752 & 4.632 \\
-5.9911 & 19.141 & -5.7414 & 11.003 & -11.854 & -0.7165 \\
-1.2036 & 1.1229 & -0.19503 & 0.61687 & -15.288 & 9.3896 \\
\end{bmatrix} \cdot 10^5 \text{ V}
\]

where the matrix \([A]\) is formed line-by-line by the found numerical values of the information coefficients \(a_{\varepsilon(j)}\) (where the \( j = \frac{1}{16} \) is row number of the matrix) of the sensor taking into account the decomposition (4), a determiner \([A] \neq 0\). The components \( \Delta[j] = U_{\text{lum}(j)} - a_U(j)U_{\text{con}} \) of the column vector \(\{\Delta\}\) in (5) are found by the previously found numerical values of the sensor control coefficients \(a_U(j): 1.0000, 0.99936, 1.0001, 1.0000, 1.0006, 1.0003\), the known value of the applied control electric voltage \(U_{\text{con}}\) on the sensor electrodes and the values of the informative electric voltages \(U_{\text{lum}(j)}\) on the electroluminophore elements in the \( j \)-th sectors of the sensor. The \(U_{\text{lum}(j)}\) are found as a result of digital processing [18-20] of the information spectrum of the intensities of the integral light signal at the output from the optical fiber taking into account the known dependences of the light output intensity \(I_{\text{lum}(j)}\) of the each \( j \)-th electroluminophore on electrical voltage \(U_{\text{lum}(j)}\) applied thereto.

5. Conclusion

The application and functional scheme of fiber-optic PEL sensors [17] embedded in polymer composite structures are presented to solve the problem of refined monitoring of "gradient" inhomogeneous strain fields inside structures. Mathematical models have been developed, settings and schemes for solving the problem of finding numerical values of transfer information and control coefficients of PEL sensors have been given. Results of numerical calculation of transfer coefficients of sensor for case of small values of gradients of diagnosed strains are presented, and system of equations (5) is formed for finding of sought diagnosed values of independent components of strain tensor \( \varepsilon^* \) in local areas of composite material along location of sensor.

Acknowledgement

The results were obtained within the framework of the State task of the Ministry of Science and Higher Education of the Russian Federation (project no FSNM-2020-0026).

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