Indicator polymer coating with built-in fiber optic piezosensor

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Abstract. A mathematical model of the functioning of the indicator polymer coating with a continuous optical fiber piezoelectroluminescent sensor built in the form of a flat spiral has been developed. The informative light signal occurs due to the mechanical-luminescent effect caused by the interaction of the piezoelectric and electroluminescent elements in the sensor. Informative characteristics are described and algorithms are given for numerical processing of sequence of output (recorded) light pulses from optical fiber of sensor for indication, location and identification of external mechanical impact and tactile effects. The results of numerical simulation of the distribution of intensity values of light outputs and locations along the length of the sensor of activated (due to external mechanical applied load and "mechanical-luminescent effect" in the sensor) sections of the electroluminescent layer of the sensor are presented; this distribution corresponds to the distribution of intensity values of light pulses at the output from the optical fiber over various time points for model geometric shapes of bodies contacting the tactile surface.

1. Introduction

In the measuring technology field, the problem of improving sensory indicator and tactile coatings (systems) for indicating, locating external mechanical impact and tactile effects measuring, such as are diagnosing the geometric, elastic and tribological characteristics of bodies in contact with the coating remains relevant. Flexible polymer sensor coatings [1-3] are used in "sensitive" systems of robotic devices [4-9], in indicator polymer coatings for detecting external impact [10-13]. Various piezoelectric materials [14, 15], particularly polyvinylidene fluoride PVDF polymer piezoelectric films [16-18], are used as sensitive elements. This work [19] presents the equivalent electromechanical model for lossy piezoelectric polymer PVDF.

Tactile sensors of matrix type [6, 20, 21] include a "matrix" as is a system of cells of elementary microelectronic sensors of force (deformation, moment), the combined information from which allows to form a holistic idea of the shape of the object. Flexible film tactile matrix sensor based on PVDF film for measurement of three components of contact force is developed in [20]. Tactile sensor with three-axis force sensing capacity is presented in [21], this sensor are based on the interface contact resistance of microstructured graphene. A flexible sensor array with 16 micro-scale capacitive units has been demonstrated based on piezoelectric PVDF film in [2]. Research results of dynamic characteristics of PVDF piezoelectric film force sensor for measuring tactile effects a steel ball are given in [22]. A capacitive microelectromechanical sensors were developed in [10, 11, 23], in particular for detect the position of the droplet [23]. Increasing sensitivity of flexible tactile sensor is based on piezoresistive effect of graphene film [24]. Interface electronic system for piezoelectric tactile sensors was investigated in [25]. Soft resistive magnetic (powdery) tactile sensors were developed in [26]. In [27] the principle,
structure design and fabrication of the sensitivity-compensated micro-pressure flexible sensor for aircraft aerodynamic surfaces were investigated.

Promising are indicator coatings based on the "mechanical-luminescent effect", it is a light output under mechanical action. This effect can be manifested for both homogeneous and composite materials with piezoelectric and electroluminescent phases [28, 29]. The mechanical-luminescent effect appears in the composite material as a result of joint interrelated phase strains. Some indicator polymer coatings include an internal strain-sensitive graphitized layer and an external "color" indicator layer of liquid crystal polymer, which changes its color depending on the amount of current passing through it. A sensor piezoelectric system [30] with a network of linear piezoelectric elements of various polarizations, which are connected to each other by local processors for switching on/off cells from the network, allows the system to automatically adapt to operating conditions and localize the probabilistic location of the diagnosed external impact, damage. The tactile sensor system [31] is based on the "decryption" of information images of high-speed photo and video recording of deformation of the system of discrete tactile elastic elements of the cantilever type from the "back" side of the transparent substrate.

The purpose is to develop a mathematical model of the functioning of the indicator polymer coating [32] with an integrated (built-in) continuous fiber optic piezoelectroluminescent (PEL) sensor [33] of complex information signals of volumetric deformation of local areas of the tactile layer for indication, location and identification of external bodies and mechanical effects (impact).

2. Mathematical model of indicator polymer coating

The two-layer indicator polymer coating (figure 1) includes a "tactile layer" and a "measuring layer" with an built-in fiber-optic PEL sensor. The tactile layer may have a smooth (flat, shaped) working contact surface (figure 2a) to find, for example, anisotropic friction coefficients between diagnosed and tactile surfaces; or tactile layer may have uniformly attached to its outer surface tactile elastic rod elements of the cantilever type ("cantilevers"), in particular with a cylindrical cross-sectional shape; the free ends of the cantilevers are working contact surfaces (figure 2b). Contact surface diagnosis is based on results of measuring the resulting forces and moments on the free end of the cantilevers (figure 2b) when using "cantilevers" tactile layer. The use of "cantilevers" tactile layer leads to an increase in the accuracy of localization of external effects as a result of a decrease in "parasitic" influence on the information signal (of strains field) of a cantilever from other "neighboring" tactile elements (cantilevers). The discreet cantilevers of tactile layer can be combined in a common continuous tactile spiral of the cantilever type with repeating the shape of the spiral of an optical fiber sensor in plane.

Generation of informative signals is performed using fiber-optic PEL sensor, which is built-in to measuring layer in the form of flat spiral, in particular, under places of fixation of cantilevers of tactile layer. The number of measuring elements with mechanical-luminescent effect "piezomaterial/phosphor" in the optical fiber PEL sensor can be different and their number is determined by the number of characteristics of a diagnosed surface by the indicator coating. In particular, "three-element" optical fiber PEL sensor for diagnosing the anisotropic friction coefficient of the surface, "six-element" for a refined analysis of the geometric shape of irregularities of the diagnosed surface of the body. PEL sensor can operate in resonance mode, in particular, under forced oscillations of its piezoelectric layer (under the influence of harmonic electric voltage $U_{con}$ on the control electrodes) to find, in particular, the temperature field of the diagnosed surface or the field of microassembles between the tactile contact surface and the diagnosed surface of the body using known dependencies of the resonance frequency of oscillations on temperature or on the value of the gap between the oscillating (tactile) and limiting these oscillations (diagnosable) surfaces.
Figure 2. Elementary cells of tactile elements with three $I_{1,3}$ (a) and six $I_{1,6}$ (b) frequency spectra of informative intensity of light signals for finding normal $F_z$ and tangent $F_x$, $F_y$ forces, rotary $M_x$ and bending $M_y$, $M_z$ moments on the "contact spot".

The substrate (base) of the indicator coating can be made in the form of a layer of "intelligent" functional materials, in particular, of magnetosensitive elastomers. As a result, the indicator coating will have functions of controlling and adapting (self-adapting) the geometry of the tactile surface to the features of the diagnosed surface, in particular, it will have functions of rotating (in the contact plane) the tactile layer and changing the main curvatures of the contact surface of the tactile layer. In the self-adaptation mode, feedback of the control parameters of the "intelligent" layer and the information data from the tactile elements can be used. The substrate may have a piezoelectric and/or magnetostrictive
layer with the function of excitation of forced oscillations, in particular: vibrational normal and tangential (to the diagnosed body surface) displacements and contact forces on the working tactile surface.

3. Results of numerical modeling
A numerical model of an indicator coating with a smooth tactile surface (plane) has been developed to indicate the shape of the body in contact with it in the form of a cube or ball (figure 3). Figure 4a shows the results of numerical simulation of normalized $I/I_{\text{max}}$ resultant (integrated by pulse width) values of intensity $I_i$ of the sequence of light pulses at the output from the optical fiber of the sensor for two cases of geometric shape of the "contact spot" in the form of a circle or square (figure 4b) of the effect of an external object on the indicator surface, where the pulse number $i = 1, n$, the total number $n$ of pulses in the group. The "contact spot" is a projection of the contact surface onto the tactile, indicator coating plane. In the sequence (figure 4a) of light pulses emanating from the optical fiber, the time interval between pulses $\Delta t_i$ increases, as the distance $\Delta z_i = c \Delta t_i$ between successive (with coordinates of centers $z_i, z_{i+1}$) activation sections (light output sections of the phosphor layer) of the sensor increases, taking into account the equality $\Delta z_i = z_{i+1} - z_i$ where the center coordinate is, $z_i = c t_i$ the moment of output from the optical fiber of the $i$-th pulse is $t_i$.

![Figure 3](image3.png)

**Figure 3.** Influence of shape on bodies on homogeneity (a) and inhomogeneity (b) of luminescence along length of sensor fragment

![Figure 4](image4.png)

**Figure 4.** Distribution of intensities $I$ of emerging light pulses by longitudinal coordinate $z$ of optical fiber (a) and design diagram (b) for various bodies: cube (□), ball (○)

The location of "contact spot" is found through the calculation of the distance $r_0$ from the center of the spot (figure 1b) to the center of the optical fiber PEL sensor spiral; the location of spiral center is known and where, for example, light pulses are recorded at the output from the optical fiber. Value $r_0$ is found through the distance $\Delta z_0$ between pulses in the central area of this pulses group (figure 4a) with
taking into account equality \( \Delta z_0 \approx 2\pi r_0 \); clarification of this formula is possible when specifying the geometric shape of the spiral. The characteristic size, for example, the diameter \( d_0 \) of the circular "contact spot" (figure 1b, figure 4b) is found through the calculation of the "total width" \( \Delta z = z_n - z_0 \) of the pulses group through the found values of the first \( z_1 \) and last \( z_n \) pulses in the group (figure 4a). The features of the longitudinal (along the sensor lines) curvature of the contact surface can be determined by analyzing the shape of individual pulses in the group (figure 4a). For example, when pressing the bottom face of the cube (figure 3a) into the indicator coating, the pulse shape is close to the rectangular shape, and when pressing the ball (figure 3b) - to the "hat" of the normal distribution.

4. Conclusion
A mathematical model of the functioning of the indicator polymer coating with a continuous optical fiber piezoelectroluminescent sensor built in the form of a flat spiral has been developed. Informative characteristics are described and algorithms are given for numerical processing of sequence of output (recorded) light pulses from optical fiber of sensor for indication, location and identification of external mechanical impact and tactile effects. In the "first approach," the location of the external impact was found through the calculation of the distance \( r_0 \) from the center of the circular "contact spot" (figure 1b) to the center of the sensor spiral. Location refinement is carried out using the scanning algorithms [33] of the strains field along the fiber-optic PEL sensor or using a three-layer "measuring layer," each layer of which has a separate spiral of the fiber-optic PEL sensor with different and known locations of the three centers. As a result, the exact location (on the tactile surface of the indicator coating) of the "contact spot" is found by three distances \( r_{01,2,3} \) from the center of the "contact spot" to each of the three centers of the spirals (with known locations inside the polymer indicator coating). The use of a three-layer "measuring layer" also makes it possible to clarify the curvatures of the contact surface of "contact spot" by analyzing the shape of the individual pulses in the group for each of the three spirals. The results of numerical simulation of the distribution of intensity values of light outputs and locations along the length of the sensor of activated (due to external applied load and "mechanical-luminescent effect" in the sensor) sections of the electroluminescent layer of the sensor are presented; this distribution corresponds to the distribution of intensity values of light pulses at the output from the optical fiber over various time points for model geometric shapes of bodies contacting the tactile surface.

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