Registration of the optical output signal of distributed mechanoluminescent impulse pressure sensors

K V Tatmyshevskiy and D D Pavlov

Institute of Information Technology and Radio Electronics, Vladimir State University, 87 Gorky Street, Vladimir, 600000, Russia

E-mail: pavlovdd84@mail.ru

Abstract. Distributed mechanoluminescent pulse pressure sensors are described in the article. The definition of mechanoluminescent sensors is given, early studies of this phenomenon and their results are also mentioned. On the basis of these studies, a mathematical model of transformation in a distributed mechanoluminescent sensor is constructed. The substantiation of the choice of a mechanophosphor for experimental studies is given. The design of a distributed mechanoluminescent sensor is described, a laboratory bench is developed and assembled. The article describes experiments to obtain and register the glow of the sensor. Conclusions are made about the results of studies and the possible use of this type of sensors.

1. Introduction

Mechanoluminescence (ML) is the ability of a material to emit light (glow) as a result of plastic deformation arising from mechanical stress on it (for example, bending, compression, shock, vibration, etc.). A feature of such sensor elements is the direct conversion of mechanical action into an optical signal, so they can be directly integrated into fiber-optic information-measuring systems and networks [1]. In [2], a detailed description of the phenomenon of mechanoluminescence was given and the materials most suitable for research were listed.

In the case of mechanoluminescence, the optical radiation of solids caused by impact or deformation is the result of structural defects in the material. Therefore, this radiation can be considered as an indicator of the amount of external impact on the material or its deformation and destruction [3]. A promising area of application of distributed mechanoluminescent sensor elements is the development of composite materials and structures with the property of self-diagnosis. It is possible to use distributed ML pulsed pressure sensors to determine the shape, size and coordinates of the impact site in a controlled area. Taking into account the high resistance to electromagnetic and radiation interference, the lack of the need to supply power to them and the possibility of a fairly simple pairing with fiber optic communication lines, these sensors can be used in robotics to make robot grips sensitive, to determine slippage [4]. It is possible to use such sensors in the skin of mobile robots and unmanned aerial vehicles (for registration of collisions with moving and stationary objects, detection of hits of bullets, shells, fragments). Mechanoluminescent sensors distributed type allows you to visualize the field distribution of pressure over the area of the investigated surface in time. These sensor elements can be used in conjunction with integrated and fiber optic devices in shock sensors, systems for recording and monitoring pulsed mechanical loads and vibrations, for example, in geophysics (seismology) and aerospace engineering.
2. General description of the distributed mechanoluminescent sensor

The object of interest in this study is a mechanoluminescent pulse pressure sensor. It is worth noting that mechanoluminescent pulse pressure sensors are of two types: concentrated and distributed (tactile). The main difference between these sensors is the area of the sensing element. The process of mechanoluminescent conversion in a concentrated sensor takes place on an area of not more than 1 mm$^2$, while the area of the sensitive element of a distributed sensor can be more than 3-5 orders of magnitude larger. Often mechanoluminescent sensors with distributed sensitivity are called tactile. But, the main difference between a distributed and a tactile sensor is that tactile means touch detection sensors, but a mechanoluminescent sensor, due to the high sensitivity threshold, can only be used to record shock effects. The sensitive element of such a sensor has a large area, and a single phosphor crystal can be called a mechanoluminescent taxel by analogy with the element of a matrix tactile sensor [5]. The glow of the phosphor of a distributed sensor caused by impact, carries information about the strength of the impact, the shape and size of the impact element at the point of contact, as well as the coordinates of the place of application of force (impact). The glow of the phosphor of a concentrated sensor carries information only about the strength of the impact.

During the research of concentrated mechanoluminescent pulsed pressure sensors, a mathematical model of converting mechanical energy into light flux was developed [2]. For mathematical description and modeling of the luminous flux of a tactile mechanoluminescent sensor, a conversion model in a distributed sensor was developed [6].

The mathematical model of the distributed ML sensor is a system of luminophore glow equations in discrete time intervals. As a result, we obtain a system of dependences of the luminous flux of luminescence $\Phi(t,S,\sigma)$ as a function of time, area, and value of mechanical stress:

\[
\begin{cases}
\Phi_{1S0} = 2C_{GC}d_{cp}k_{V}S_{0} \frac{\eta}{\tau_{a}} \exp\left(-\frac{t}{\tau_{a}}\right) \int_{0}^{t_{1}} r_{int}(t) N_{mD}(t) U_{D}(t)d(t) \\
N_{mD}(t)U_{D}(t)d = \frac{3}{4|b|} \varepsilon_{p}^{p} \\
S_{0} = \int_{t_{1}=t_{0}}^{t_{1}=t_{1}} \left(f_{1}(x) \pm f_{2}(x) \pm \cdots \pm f_{n}(x)\right) \\
\sigma = \sigma_{a} \times sin\left(\frac{\pi}{t_{a}}\right) \\
\sigma_{a} = \frac{P}{S_{0}} \\
t \in [t_{0}; t_{1}]
\end{cases}
\]
\[
\phi_{1Sn} = 2C^v_{GC}d_{cp}k_\nu S_1 \frac{\eta}{t_s} \exp\left(-\frac{t}{t_s}\right) \int_{r_{int}(t)}^{t_{n-1}} r_{mD}(t)U_D(t)d(t) \\
N_{mD}(t)U_D(t)d = \frac{3}{4|\vec{b}|}\dot{\varepsilon}_1^p \\
S_0 = \int_{x_{t=tn-1}}^{x_{t=tn}} (f1(x) \pm f2(x) \pm \cdots \pm fn(x)) \\
\sigma = \sigma_a \times \sin\left(\frac{\Delta t}{t}\right) \\
\sigma_a = \frac{P}{S_0} \\
t \in [t_{n-1}; t_n]
\]

where \(\eta\) - quantum energy of light; \(\tau\) - lifetime of an excited state; \(t_s\) - duration of the excitation of the glow center (GC) by a pressure pulse \(\sigma(t)\); \(r_{int}\) - the radius of interaction of the dislocation with the GC; \(N_{mD}\) - average density of mobile dislocations; \(U_D\) - the average velocity of dislocations along the dislocation array; \(|\vec{b}|\) - the Burgers vector module characterizing the region of distortion of the crystal lattice by a dislocation of a certain type; \(\dot{\varepsilon}_1^p\) - plastic strain growth rate; \(C^v_{GC}\) - volume concentration of GC; \(V\) - total volume of crystal grains; \(N_{D}\) - total dislocation density; \(S\) - sensor area; \(t\) - current time.

Zinc sulfide activated by manganese was chosen as the mechanoluminophore as the material most suitable for research [3, 7, 8].

3. **Design of a distributed ML pulse pressure sensor**

Technically distributed ML sensor was made in the form of a multilayer structure, shown in figure 1.

![Figure 1. The structure of a distributed mechanoluminescent sensor.](image-url)
The sensor is a film mechanoluminescent sensor element made of ZnS: Mn, which is tightly sandwiched between a solid transparent base and a non-transparent film protective coating. It is very important to ensure the structural hardness so that on the free surface of a solid, mechanical stresses are zero, therefore it is not practical to apply a mechanoluminescent sensitive element to the free surface of structures [9].

4. Description of the stand for the research of distributed ML sensor elements

For the research of distributed mechanoluminescent sensing elements of pulsed pressure, a laboratory test bench was designed and assembled. The layout of the test bench with a ML sensor of a distributed type is shown in figure 2.

![Figure 2. Scheme of a test bench with a ML sensor of a distributed type.](image)

The appearance of the laboratory bench is shown in figure 3. Figure 4 shows the schematic representation of the placement of a distributed mechanoluminescent sensor on a test bench.

![Figure 3. Laboratory stand for the research of distributed ML sensors.](image)

![Figure 4. Schematic illustration of a sensor installation on a test bench.](image)
The light emission of the phosphor is recorded by a digital video camera through a closed optical channel, which is a hollow cone of height \( H \) (the height of the cone depends on the viewing angle of the camera’s lens \( \alpha \) and the area of the sensitive element). The area of the sensor element is \( 20 \text{ cm}^2 \).

5. The results of experimental researches
The main purpose of the experiment was to register the luminescence of the ML sensor under mechanical impact. The mechanical effect was divided into several types. The first is the impact of a simple body (drop on a sensor element of a metal ball weighing 170 grams from a height of 1 meter). Figure 5 shows an inverted image of the frame with a pronounced round glow.

![Figure 5. The light emission of the ML sensing element when a metal ball falls on it.](image)

The second experiment is the impact by elements of complex shape. Figure 6 shows an inverted image of the luminescence frame of a mechanophosphor upon impact with a flat metal ring (the mass of the ring is 230 grams, the drop height is 1 meter). As can be seen from figure 6, the glow has a clear annular shape.

![Figure 6. ML sensor light emission when a metal ring falls on it](image)

The third experiment was the detection of motion on the surface of the sensor. To do this, a metal ball was rolled along the surface of the sensor and when the hand was pressed lightly, the movement of
A bright luminous dot was clearly visible on the screen. Figure 7 shows the superposition of the phosphor luminescence frames during the rolling of a metal ball over the surface of a mechanoluminescent sensor. The combination of the frames of the ball movement:

Thus, the possibility of using mechanoluminescent sensing elements with area-distributed sensitivity for visualization of pulse pressure fields with different time and amplitude parameters has been experimentally proved. It is also possible to register external mechanical effects and determine the place of impact, impact force, size and shape of the striking body.

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