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LIQUID CRYSTAL SENSORS OF PRESSURE, ACCELERATION AND VIBRATION: PHYSICAL BACKGROUNDS AND POSSIBLE APPLICATION.

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The physical backgrounds of use of liquid crystal cells (LCC) as sensors of pressure, acceleration and vibration are discussed. The theoretical description of an orientation and light intensity changes induced by a low-frequency pressure gradient is carried out in the framework of a linear approximation. The analysis of the obtained theoretical and experimental results allows to propose the methods of a control of technical parameters of liquid crystal sensors. The possible construction of a sensor of pressure difference is presented.

Among the various applications of liquid crystals in modern industry those concerning the usage of these materials as sensitive elements of sensors of mechanical stresses and vibrations have not got yet an essential development. It can be partly explained by a rather complex character of physical processes, which take place in liquid crystal media under the action of mechanical perturbations of different frequencies and amplitudes. In particular, different new types of instabilities (depending on experimental parameters) were observed in liquid crystal layers [1]. It can be understood taking into account the connection between the velocity gradients and the local orientation of an optical axis, described by an unit vector - the director **n**. Indeed, this connection is a fundamental property of nematic liquid crystals (NLC), which can be used for an elaboration of high sensitive liquid crystal sensors. The absence in nematic liquid crystals (as in simple liquids) of a long-range positional order leads to the high mobility of these systems under the action of weak mechanical stresses (pressure gradients, for example). At the same time NLC have a long-range orientation order, which can be changed by magnetic (or electric) field application or by velocity gradients [2]. In relatively thin layers (~1…300µ) usually used in optic devices the long-range order is influenced by boundaries too. Using the special treatment of solid surfaces interacting with NLC, different boundary orientation can be achieved. The existing experimental data and the theoretical calculations have shown that homeotropic boundary conditions (**n** is normal to the boundaries) are most preferable for high sensitive sensor elaboration. So, we restrict the results presented in the report to this case.

Let us consider the behavior of initially homeotropic layer of nematic liquid crystal distorted by some mechanical perturbation (by pressure gradient $G(t) = \partial p(t)/\partial x = (\partial p_m/\partial x)*\cos \omega t$, for example) in the presence of external electric field **E** (fig.1).

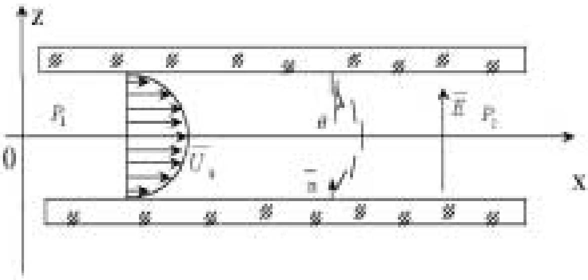

Fig. 1. The flow induced variations of LC structure in homeotropic cell; E- electric field strength; $P_1>P_2$

For strong boundary anchoring the solution of the dynamical equations for the angle $\theta(z,t)$ in the framework of linear hydrodynamic theory can be written as [3]:

$$\theta(\tilde{z},\tilde{t}) = \theta r(\tilde{z})\cos\tilde{t} + \theta i(\tilde{z})\sin\tilde{t} \qquad (1)$$

where $\tilde{t} = \omega t$ and $\tilde{Z} = \frac{Z}{h}$ - dimensionless parameters ;

$$\theta r(\tilde{Z}) = -\frac{\Delta p_m}{\Delta X}\frac{d}{\eta_2\omega\left[\left(\frac{\omega_E}{\omega}\right)^2 + m^2\right]}\bullet$$

$$\bullet\left\{\left(\frac{\omega_E}{\omega}\right)\left[\tilde{Z}+\frac{1}{2}\frac{\cos k_2\left(\tilde{Z}+\frac{1}{2}\right)\cosh k_1\left(\tilde{Z}-\frac{1}{2}\right)-\cos k_2\left(\tilde{Z}-\frac{1}{2}\right)\cosh k_1\left(\tilde{Z}+\frac{1}{2}\right)}{\left(\cosh k_1-\cos k_2\right)}\right]-m\bullet\right. \quad (2)$$

$$\left.\bullet\left[\frac{1}{2}\frac{\sin k_2\left(\tilde{Z}-\frac{1}{2}\right)\sinh k_1\left(\tilde{Z}+\frac{1}{2}\right)-\sin k_2\left(\tilde{Z}+\frac{1}{2}\right)\sinh k_1\left(\tilde{Z}-\frac{1}{2}\right)}{\left(\cosh k_1-\cos k_2\right)}\right]\right\}$$

$$\theta i(\tilde{Z}) = -\frac{\Delta p_m}{\Delta X}\frac{d}{\eta_2\omega\left[\left(\frac{\omega_E}{\omega}\right)^2 + m^2\right]}\bullet$$

$$\bullet\left\{\left(\frac{\omega_E}{\omega}\right)\left[\frac{1}{2}\frac{\sin k_2\left(\tilde{Z}-\frac{1}{2}\right)\sinh k_1\left(\tilde{Z}+\frac{1}{2}\right)-\sin k_2\left(\tilde{Z}+\frac{1}{2}\right)\sinh k_1\left(\tilde{Z}-\frac{1}{2}\right)}{\left(\cosh k_1-\cos k_2\right)}\right]+m\bullet\right. \quad (3)$$

$$\left.\bullet\left[\tilde{Z}+\frac{1}{2}\frac{\cos k_2\left(\tilde{Z}+\frac{1}{2}\right)\cosh k_1\left(\tilde{Z}-\frac{1}{2}\right)-\cos k_2\left(\tilde{Z}-\frac{1}{2}\right)\cosh k_1\left(\tilde{Z}+\frac{1}{2}\right)}{\left(\cosh k_1-\cos k_2\right)}\right]\right\}$$

$$k_1 = \sqrt{\frac{1}{2}\left[\frac{\omega_E}{\omega_0}+\sqrt{\left(\frac{\omega_E}{\omega_0}\right)^2+m^2\left(\frac{\omega}{\omega_0}\right)^2}\right]} \quad (4)$$

$$k_2 = \frac{\frac{1}{2}m\left(\frac{\omega}{\omega_0}\right)}{\sqrt{\frac{1}{2}\left[\frac{\omega_E}{\omega_0}+\sqrt{\left(\frac{\omega_E}{\omega_0}\right)^2+m^2\left(\frac{\omega}{\omega_0}\right)^2}\right]}} \quad (5)$$

$$m = 1-\frac{(-\alpha_2)}{\eta_2}\bullet\frac{1}{1-\lambda} \quad (6) \qquad \lambda = \frac{\alpha_3}{\alpha_2} \quad (7)$$

α_i – the Leslie coefficients, η_2 – the shear viscosity coefficient,.

The degree of influence of an electric field on the solutions obtained above depends on relative values of three frequencies:

ω - the frequency of external force,

$\omega_0 = \dfrac{k_{33}}{d^2 \gamma_1}$ - the frequency of orientational relaxation in the absence of the electric field and

$\omega_E = \dfrac{\varepsilon_0 \Delta\varepsilon E^2}{\gamma_1}$ - the analogous frequency in the presence of the electric field ($\gamma_1 = \alpha_3 - \alpha_2$ – the rotational viscosity coefficient, $\Delta\varepsilon$ - the electric permittivity anisotropy, K_{33} – the Frank module of an orientation elasticity).

It is essentially from the practical point of view that in a linear approximation the angle θ is proportional to an amplitude G_m of the pressure gradient. In this case the maximal value of the phase difference δ_m between the extraordinary (e) and the ordinary (o) rays, which can be calculated from the changes of intensity of polarized light passing through the liquid crystal layer has to vary as:

$$\delta_m = A\,(G_m)^2 \qquad (8)$$

independently on the value of electric field.

Equation (3) can be considered as the basic one for an elaboration of high sensitivity liquid crystal sensors of differential pressure. There are the two main possibilities to control the sensitivity and the dynamical range of such devices. The first one is connected with the a very strong dependence of the A coefficient on the thickness of liquid crystal layer (in the absence of electric field $A \sim h^7$). It leads to essential changes of the optical response I(t) on harmonically changing pressure gradient at relatively slight thickness variations. The examples of such dependencies, obtained for well studied liquid crystal MBBA are presented in figure 2. The experiments were fulfilled using the He-Ne laser (λ= 0.63μ) and the liquid crystal cell with a varying value of h [4] placed between the crossed polarizers oriented at 45^0 relatively to the flow direction (in this case the amplitude of an optical response $I = I_0 \sin^2\delta/2$ is the maximal one). It is of importance, that the linear theory satisfactory describes the experimental dependencies I(t) using the measured values of material coefficients of MBBA [5]. So one can predict the behavior of liquid crystal sensors under varying of external conditions (the temperature, for example).

The second way to control the technical parameters of liquid crystal sensors is the usage of electric voltage applied to the liquid crystal layer. It can stabilize the orientation structure of liquid crystals with a positive value of $\Delta\varepsilon$ and effectively increase the value of pressure induced phase difference δ [6] (in the case of strong fields $A \sim U^{-4}$). The high absolute value of this parameter ($\Delta\varepsilon \geq 10$) for modern liquid crystal mixtures is enough to elaborate the liquid crystal sensors with the electrically controlled technical characteristics (for example, the dynamical diapason, which is rather narrow in the absence of the field can be extended up to about 100 using relatively low ($\leq$ 50 V) controlling voltage).

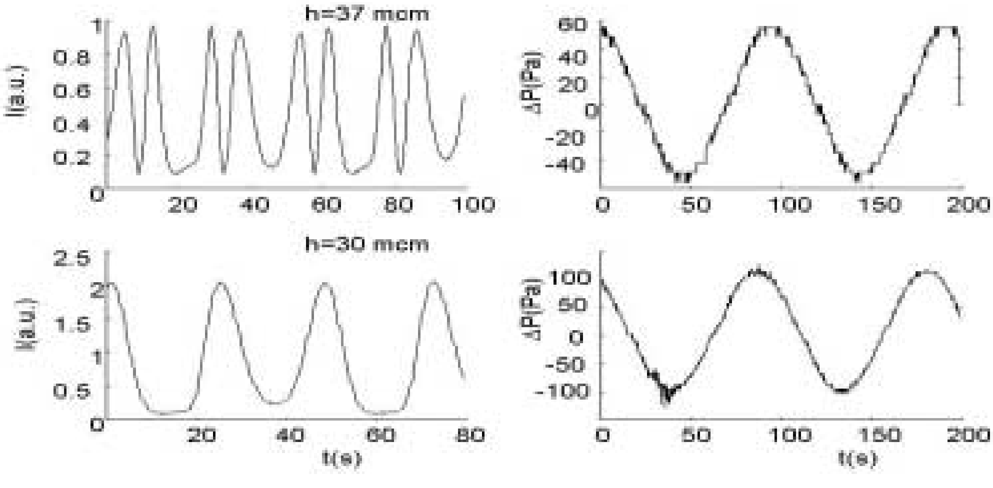

Fig.2. The optical response I(t) of LC cell on pressure difference ΔP(t) at variable thickness of LC layer (h).

The example of a possible construction of a liquid crystal sensor of differential pressure [7], which combines the possibilities mentioned above is presented in fig.3. A very high sensitivity of liquid crystal layers to the pressure gradient (in experiments we have registered the pressure gradients about 1 Pa/m) permits to search for different applications of liquid crystal sensors. They are mainly connected with a registration of low frequency mechanical perturbations. In particular, the liquid crystal sensors of differential pressure can be used to register the parameters of slow flows of liquids or gases [8] including the flows in pipelines. In biomedical applications the usage of liquid crystal sensors for a registration of human breathing is possible, especially for a distant study of this process [9].

The analogous sensors can be also effectively used for a detection of slight infra sound vibrations or for a measuring of angular and linear accelerations. In all cases, mentioned above a high sensitivity and a control of parameters can be achieved at relatively small sizes and low energy consumption of sensors.

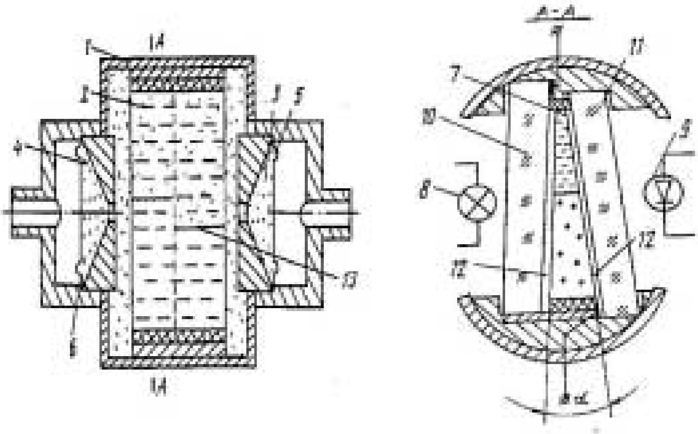

Fig. 3. The possible construction of the liquid crystal sensor: 1- a body; 2- nematic liquid crystal; 3,4 - chambers; 5,6 - membranes; 7 - a capillary; 8 - a polarized light source; 9 -a photodetector; 10,11 - glass plates; 12 - current-conducting coating, 13 - a boundary between distorted and undistorted regions of a liquid crystal.

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