USE OF DIELECTRIC SENSORS IN RECORDING PRESSURE PULSES

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Dielectric pressure sensors are presently used by many researchers to record the profiles of pressure pulses in solids produced by shock or explosive loading. A lack of understanding of the physical principles of sensor operation and unique features of sensor application may be the cause of conflicting estimates of sensor capability and reports of unreliability of measurements performed with such sensors. The present study will review and present results from the latest studies performed at the Institute of Strength Problems, Academy of Sciences of the Ukrainian SSR, on design and application of dielectric sensors for pressure pulse recording in solids. The major results of the sensor studies have been published in [1-5].

Dielectric pressure sensors were initially developed for recording the pressure pulse acting in the plane of the front of planar loading waves. The simplest technological realization of such a sensor is in the form of a planar capacitor (Fig. 1a), with central electrode 1 and output lead located between two layers of dielectric film 2, and second electrode 3 (surfaces of conductive metal materials) grounded. For use with nonmetallic materials the second electrode is formed by a thin metal foil, folded over the dielectric films (not shown in Fig. 1). To increase resolution speed a single dielectric film is used, pressed together with the central electrode against the material under study by a plate 4 of some material with acoustical rigidity approximately equal to the acoustical rigidity of the dielectric material, for example, Plexiglas (Fig. 1b).

Pressure measurement relies on recording the change in sensor capacitance upon compression. This capacitance C_d is charged from a constant voltage source U_0 through a resistance R which is so high that the effect of the charging rate during the entire recording time t_r is insignificant:

$$RC \gg t_r, \tag{1}$$

where $C = C_d + C_{circ}$, C_{circ} being the stray circuit capacitance (of connecting leads and the input circuit of the recording device).

As the sensor is compressed the capacitor charge $Q = C_0U_0 \approx CU$ (the subscript 0 denotes the initial value) remains practically constant (we neglect the conductance of the dielectric film), and the change in capacitance produced by compression of the dielectric leads to a change in the voltage ΔU across the sensor electrodes, which is recorded by a high input impedance device, with input impedance R_{in} also satisfying Eq. (1). Depending on the concrete experimental conditions, the dielectric sensor could be connected directly to the vertical deflection plates of an oscilloscope tube by a short length of cable (Fig. 1c), or through a cathode follower (CF) or high input impedance amplifier (Fig. 1d), allowing the signal to be transmitted a considerable distance over a matched line. For a short line section of length L, not matched to the input impedance of the recording device, transient processes can be neglected if their duration $t = (5\text{-}10)L/C_{em}$ (where C_{em} is the velocity of an electromagnetic wave in the line) is negligibly small in comparison to the recording time, $t \ll t_r$.

The change in voltage across the sensor electrodes is given by the expression [3]

$$\Delta U = -\int_0^p \frac{C_0 U_0}{C^2} \frac{dC}{dp} dp,$$

where p is the pressure value in the compression wave.

The sensor electrical signal amplitude is proportional to the value of the polarizing voltage, and is approximately inversely proportional to the circuit capacitance

$$\Delta U = -(U_0 \Delta C_d / C_0)(1 + \Delta C_d / C_0)^{-1},$$

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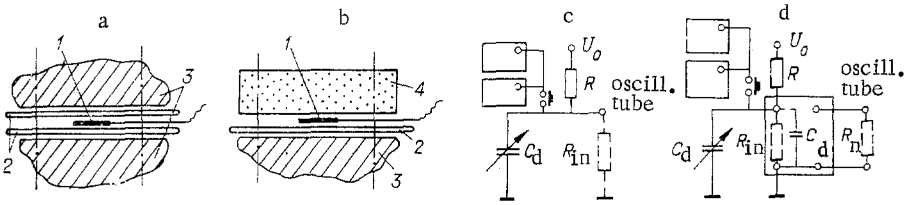

Fig. 1

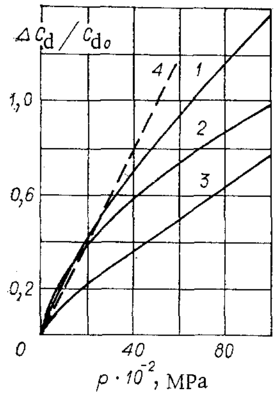

Fig. 2

permitting high sensitivity to be achieved. Thus, for a polarization voltage U_0 = 800 V a sensor with a triacetate film 0.2 mm thick has a sensitivity of 0.24 V/MPa if the low pressure is increased to 10,000 MPa given a low circuit capacitance ($\Delta C_d \approx C_0$). A nonlinear sensor calibration curve $\Delta C_d/C_{d0} = f(p)$ does not decrease measurement accuracy or complicate oscillogram processing. As was shown in [3], the calibration curve can be described satisfactorily by the expression

$$f(p) = \frac{\Delta C_d}{C_{d\,0}} = \left(1 - \frac{1}{\varepsilon_0}\right)\left(\frac{np}{\rho_0 a_0^2} + 1\right)^{2/n} + \frac{1}{\varepsilon_0}\left(\frac{np}{\rho_0 a_0^2} + 1\right)^{1/n} - 1,$$

where C_{d0}, ΔC_d are the initial sensor capacitance and the change under pressure ε_0, ρ_0 are the dielectric permittivity and density of the dielectric film; n, a_0 are the exponent in the equation of state and initial speed of sound in the dielectric film. This expression is based on calculating the change in sensor capacitance produced by both the decrease in film thickness and the change in dielectric permittivity ε_0. It should be noted that initial linear calibration curves for a number of dielectric materials [2] were based on an insufficiently reliable calibration technique and cannot be used in accurate experimental studies. Moreover, possible differences in film characteristics related to chemical composition, manufacturing technique, etc. require individual calibration of each group of films used.

A high polarizing voltage is employed in order to increase measurement stability. At a low U_0 value shock polarization processes in the dielectric film as the loading wave passes through affect the signal, and these processes do not characterize the pressure profile, leading to quantitative and qualitative distortions of the signal amplitude and form. Experimental studies of 0.2-mm-thick triacetate film have shown that the presence of the electric field produced by a polarizing voltage $U_0 \geqslant 400$ V suppresses shock polarization (when the field polarity is reversed the signal undergoes no change in amplitude or form). However in some cases a high value of polarizing voltage is an obstacle to practical sensor use. Reduction in voltage and use of a thinner film avoids this difficulty, but the danger of film breakdown at weak points caused by microdefects, thickness variations, and other imperfections increases. Thus it is not desirable to use sensors with lavsan films thinner than 0.04 mm. Microdefects in such thin films cause breakdown during preparation for the experiment (when the polarizing voltage U_0 = 100 V is applied) or charge leakage during recording, leading to elevated signal levels.

These phenomena are absent when lavsan film 0.06 mm thick is used. Figure 2 shows calibration curves for a sensor (1, 0.2-mm triacetate film; 2, 0.14-mm celluloid film; 3, 0.06-mm lavsan film). Line 4 is taken from [6] for a sensor with 0.04-mm lavsan film.

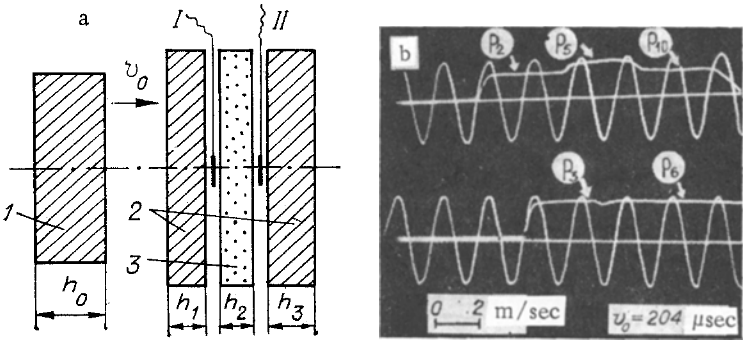

Fig. 3

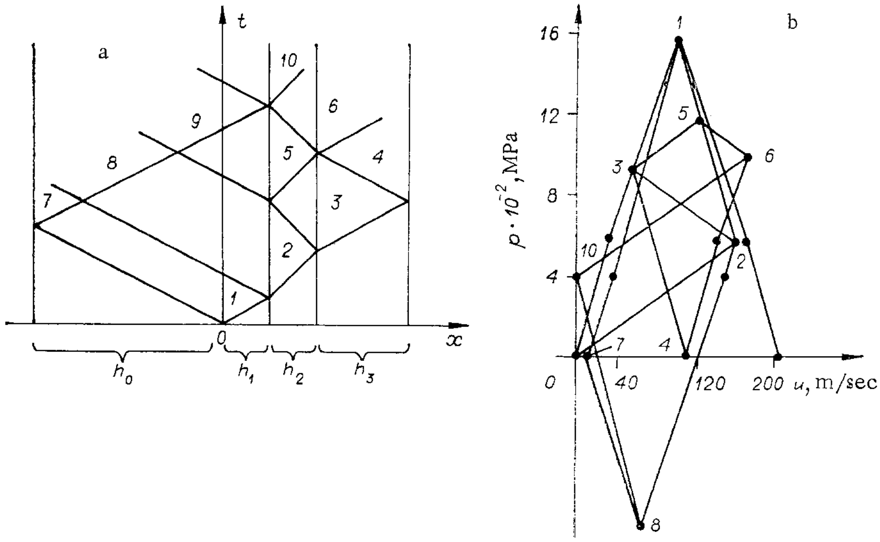

Fig. 4

Use of thick dielectric layers [7] produces an increase in the transient time for equalization of pressure within the sensor and surrounding material and requires an increase in polarizing voltage in proportion to the thickness. In a manner similar to a sapphire sensor, such a sensor connected to a low impedance R (short circuit method) which satisfies the condition $RC \ll t_r$ allows recording of the loading pulse on the specimen-sensor surface over the time during which the pressure pulse passes through the dielectric layer. It has been established experimentally that a sensor with 10-mm-thick Plexiglas dielectric and polarizing voltage U_0 = 1000 V satisfactorily records the loading wave profile on the steel–Plexiglas boundary, produced by reflection from the boundary of an elastoplastic wave in the steel, including the unloading wave profile. A calibration curve obtained with a thin dielectric film can be used to process the oscillograms.

Numerous experimental studies and analysis of dielectric sensors use for recording single pressure pulses have established that at a sufficiently high polarizing voltage, which suppresses shock polarization in the dielectric during the loading wave, processing of the oscillograms with a calibration curve $\Delta C_d/C_{d0} = f(p)$ provides a reliable determination of both the amplitude and profile of the pressure pulse.

To study the unique features of repetitive recording of preloading or unloading waves with dielectric sensors a special series of experiments were performed, as diagrammed in Fig. 3a. A planar loading wave, produced by collision of block 1 of D16 alloy, h_0 = 20 mm thick, against the layered aluminum 2–Plexiglas 3–aluminum 2 specimen (layer thicknesses: h_1, h_2, h_3 – 6, 6, 10 mm), was recorded by dielectric sensors at the two metal–Plexiglas surfaces. Oscillograms of the sensor signals are shown in Fig. 3b (0.06-mm thick lavsan film used in sensors). Diagrams of the (x – t) and (p – u) wave processes in the specimen are shown in Fig. 4. Calculation of the pressure from these diagrams using an elastoplastic material model produced satisfactory agreement with the experimentally measured p_3, p_6. In processing the oscillograms a calibration curve obtained for single time compression was used.

The reduction in sensor signal upon recording a preloading wave noted in [6] can be explained by nonlinearity of the sensor calibration curve. This is confirmed by the fact that the ratio of the signal amplitudes related to passage of the first loading wave and the subsequent preloading wave on the oscillogram shown in that study correspond to calibration curve 3 of Fig. 2.

The calibration curve employed in [6] differs sharply from that presented in the present study, apparently because of charge leakage during the recording process due to use of a 0.4-mm lavsan film.

It should be noted that use of a dielectric sensor to record pressure in a plane parallel to the wave front produces single-axis film deformation and leaves the area of the sensor electrode constant. When pressure in diverging waves or in a plane which deforms under loading is recorded, it is necessary to consider both the change in electrode area and the change in dielectric thickness (the number of dipoles in the layer forming the planar capacitor). An example of using a dielectric sensor to record pressure in a plane perpendicular to the front of a plane wave was presented in [5]. Nor is it difficult to use a sensor to record pressure in the plane of the front of a diverging cylindrical or spherical wave, when the deformation in the sensor plane can be calculated from the oscillogram produced.

Thus, on the basis of previously performed and present studies, we may conclude that the dielectric sensor is a suitable device for recording pressure profiles, including those of preloading and unloading waves, given the existence of a unique calibration curve which defines the change in capacitance with pressure.

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