The decrease in the ultimate strength of organic glasses (polycarbonate, polymethyl methacrylate) is caused by polymer degradation during its operation. Exposure to ultraviolet and solar radiation, cyclic wind and snow loads, temperature drops and temperature gradients arising from opposite sides of the glass are all the main causes of degradation [1-3]. The rate of degradation of organic glasses depends on the combination and intensity of the factors involved.

The latter is virtually impossible to take into account when evaluating the resource of such glasses. In this regard, the task of monitoring changes in the tensile strength of organic glasses during their operation is relevant.

Currently, there are several main methods for monitoring the tensile strength of monolithic organic glasses: optical methods, measurement of mechanical stresses using tensor sensors, ultrasonic methods, X-ray method, and a number of others [4]. The most appropriate method for monitoring changes in the tensile strength of monolithic organic glasses is based on measuring the piezoelectric stress that occurs in a polar polymer under mechanical influences on it [4, 5]. The mechanism of the piezoelectric effect in organic glasses is associated with the polarization of macromolecules, which occurs when their relative positions change, for example, as a result of external mechanical influences [6, 7]. Moreover, the magnitude of the piezoelectric voltage is related to the structure of the material. Structure changes (for example, the beginning of cracking) are manifested in a decrease of the piezoelectric voltage value typical for a given mechanical load at a given geometry and material of organic glass. The circuit implementation choice for the piezoelectric voltage measuring is based on the specific requirements fulfillment due to operating conditions. They are, for example, a dynamic range of ~ 60 ÷ 70 dB, noise immunity, measurement error no more than 10% and a number of others [4, 6]. The use of amplitude measurement methods, for example, using voltmeters, requires high input resistances and the absence of input quasi-constant measuring currents, which lead to a change in the charge capacity of the measuring electrodes. The autogenerating method is one of the promising methods for controlling the
piezoelectric voltage [8]. The aim of this work is to study the autogenerating method for controlling the value of piezoelectric voltage using a model of its circuit implementation.

The proposed autogenerator method for monitoring piezoelectric voltage is based on a change in the frequency or phase of oscillation of the autogenerator when the measuring reactivity is included in its oscillatory circuit [9]. In this case the capacitance formed by two electrodes deposited on opposite surfaces of organic glass is such an element [5]. Mechanical action on organic glass leads to the appearance of an induced potential difference on these electrodes due to the emerging piezoelectric effect. A voltage change across the capacitance of the oscillatory circuit should not affect the operation mode of the autogenerator active element. It is worth paying attention when choosing an autogenerator schematic diagram. In addition, the requirements for the frequency stability of the measuring autogenerator remain high to ensure the measurement error is no more than 10% [10]. Thus, the Klapp autogenerator is used as a measuring generator, since it is characterized by increased frequency stability. Schematic diagram models of the measuring and reference oscillators are shown in figure 1. The analysis of the circuits operation was carried out in the Micro-Cap 9.0 application package.

Figure 1. Schematic diagrams of reference (a) and measuring (b) Klapp autogenerators.

An autogenerator built on transistors J6, Q4, Q5 is used as a reference signal recorded in node 10. The capacitance charge of the C45 sensor from the constant voltage source V3 is provided in the generator, built on the transistors J7, Q6, Q7, through the circuit R69 and the key S1. The piezoelectric voltage appearance is simulated on the capacitance C45, formed by measuring electrodes located on opposite sides of monolithic organic glass [5]. The moment of turning on the S1 key is set by the chain R68 and C49. The time constant of the charging circuit was 40 μs. The output oscillation of this autogenerator was filmed at node 20. It should be noted that the operating point position of the transistor J7 does not change when the voltage on it changes from the V3 source in the proposed circuit for
switching on the measuring reactivity C45. In its turn a constant voltage that sets the operating mode of
the active element J7 is not appli-

cated to the measuring capacitance C45. Thus, the change in the
piezoelectric voltage arising in organic glass under the action of external mechanical influences causes
a change in the constant voltage component on the capacitance C45. The R70 resistance is used to
establish the same parameters of the output oscillations of the reference and measuring autogenerators
in the absence of piezoelectric voltage (V3 = 0). The sampling step in the simulation was 200ps.
Transient processes of $V_{10}$ and $V_{20}$ oscillation formation are completed within 400 ± 40 μs. Figure 2
shows typical oscillograms with V3 equal to 0 V and 5 V.

![Figure 2. Typical oscillograms of oscillation $U$: (a) - V3 = 0V; (b) - V3 = 4V.](image)

The simulation results show that the change in the autogenerator frequency depending on the V3
voltage is extremely insignificant, and amounts to ~ 3 kHz /V. Phase detection of harmonic signals, as
a rule, uses the analysis of a signal proportional to the product of the investigated with a reference having
the same frequency:

$$U = U_{10} \cdot U_{20} = U_0 \sin(\omega t) \cdot U_0 \sin((\omega + \Delta \omega)t + \varphi) =$$

$$= \frac{U_0^2}{2} \left[ \cos(\Delta \omega + \varphi) - \cos((2\omega + \Delta \omega) + \varphi) \right]$$

In the simulation $U_0 = 2.75$ V. After filtering high frequencies ($2\omega$) and in the smallness approximation
$\varphi$:

$$U = \frac{U_0^2}{2} \left[ \cos(\Delta \omega) \cdot \cos(\varphi) \right]$$

The phase difference between the oscillations of the reference and measuring autogenerator in the
range of typical values of piezoelectric voltages 0 ÷ 5 V [5] is insignificant and amounts to ~ 0.7 deg /V.
Thus, the sensitivity of the measuring autogenerator frequency and phase to the magnitude of the
piezoelectric voltage is insignificant. Therefore, high frequency stability (no worse than $10^{-5}$) of
autogenerators (figure 1) is required to determine the magnitude of the piezoelectric voltage from these
values, which is unattainable for such circuits in practice.

Figure 3 shows the dependence of changes in the beat frequency of oscillation (1) with a change in
the piezoelectric voltage.

Deviation from linearity (figure 3) occurs with increasing frequency $\omega$ of the generator. Lowering of
frequency $\omega$ leads to a decrease in the measuring characteristic slope and, consequently, to a
measurement sensitivity decrease. In addition, the beat frequency becomes close to the industrial noise
frequencies with a small amount of mechanical deformation of organic glass [5]. In this regard, when
choosing the frequency $\omega$, you should limit yourself to the range of 4÷9 MHz. As a result of signal
conversion (1), the frequency in the processed oscillations spectrum is doubled up to 8÷18 MHz. This
should be considered when using the signal processing unit. This imposes a lower limitation on the
speed of the ADC and microcontroller when building a digital circuit for extracting and processing the beat signal. So, the clock frequency of the microcontroller must be at least 50 MHz. The using analog circuit for multiplying oscillations (1) with the separation of the beat frequency given, for example, in [11], will reduce these requirements. The simulation results show that the beat frequency lies in the range of 0 ÷ 10 kHz when the piezoelectric voltage changes in the range of 0 ÷ 5 V. High speed ADC and microcontroller are not required when using digital methods of processing this waveform.

**Figure 3.** Beat frequency change with change of V3. Frequency ω: (1) - 2 MHz; (2) –5MHz; (3) – 7MHz; (4) –10MHz.

**Figure 4.** Typical dependences of the response force to an external action and the corresponding change in the autogenerators beat frequency of oscillations.
To verify the adequacy of the simulation results of the proposed scheme for implementing the autogenerator method for measuring piezoelectric voltage, experimental studies were carried out. The experimental research scheme is similar to operation [5]. The magnitude measurement of the piezoelectric voltage was carried out by an autogenerating method. Klapp's measuring and reference autogenerators are implemented according to the scheme shown in figure 1, the output oscillation multiplier is implemented according to the scheme given in [11]. The beat signal was processed using an Arduino microprocessor. The beat frequency \( f \) was normalized to its maximum value, which was \( 5 \pm 0.5 \) kHz; the response force \( P \) was normalized to the maximum value of \( 776.75 \pm 77.6 \) N. The results of experimental studies are shown in figure 4.

The frequency stability of the reference and measuring autogenerators at a piezoelectric voltage \( V_3 = 1\) V was estimated by the method given in [12] and was \( \sim 10^{-2} \). Such stability, on the one hand, is not enough to measure the piezoelectric voltage magnitude, on the other hand, it is sufficient to control the tensile strength of monolithic polycarbonate.

Thus, the autogenerating method can be used to control the ultimate strength of organic glasses by monitoring the reference and measuring autogenerators beat frequency of the oscillations. In this case, it is necessary to provide galvanic isolation of the measuring capacitance in the oscillatory circuit of the measuring autogenerator and the power supply circuits of the active element. The most expedient frequency range of autogenerators (reference and measuring) according to the Klapp scheme is 4÷9 MHz, followed by an analog circuit for extracting the beat signal of these autogenerators. Experimental studies have confirmed the adequacy of the modeling. Frequency stability \( \sim 10^{-2} \) is sufficient to control the tensile strength of monolithic polycarbonate glasses.

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