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ПЕТРОЗАВОДСКИЙ ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ (РОССИЯ)

# АРХИТЕКТУРНО-СТРОИТЕЛЬНЫЙ КОМПЛЕКС: ПРОБЛЕМЫ, ПЕРСПЕКТИВЫ, ИННОВАЦИИ

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АРХИТЕКТУРНО-СТРОИТЕЛЬНЫЙ КОМПЛЕКС: ПРОБЛЕМЫ, ПЕРСПЕКТИВЫ, ИННОВАЦИИ [Электронный ресурс] : электронный сборник статей международной научной конференции, посвященной 50-летию Полоцкого государственного университета, Новополоцк, 5–6 апр. 2018 г. / Полоцкий государственный университет ; под ред. А. А. Бакатовича, Л. М. Парфеновой. – Новополоцк, 2018. – 1 электрон. опт. диск (CD-ROM).

Рассмотрены вопросы архитектуры и градостроительства в современных условиях, прогрессивные методы проведения инженерных изысканий и расчета строительных конструкций. Приведены результаты исследований ресурсо- и энергосберегающих строительных материалов и технологий, энергоресурсосберегающие и природоохранные инновационные решения в инженерных системах зданий и сооружений. Рассмотрены организационные аспекты строительства и управления недвижимостью, проблемы высшего архитектурного и строительного образования.

Для научных и инженерно-технических работников исследовательских, проектных и производственных организаций, а также преподавателей, аспирантов, магистрантов и студентов строительных специальностей учреждений образования.

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# КОНТРОЛЬ МЕХАНИЧЕСКИХ НАПРЯЖЕНИЙ ВНУТРИ ДЕФОРМИРУЕМЫХ СРЕД ПЬЕЗОПРЕОБРАЗОВАТЕЛЯМИ

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*Пьезопреобразователи предназначены для решения сложной научно-технической задачи: контроля и исследования напряжённого состояния внутри деформируемых сред. Проведена проверка работоспособности пьезопреобразователей при натурных измерениях механических напряжений внутри образцов материалов. Рассмотрен принцип работы преобразователей и приведены результаты экспериментальных исследований.*

*Ключевые слова: преобразователь; пьезоэлектрический эффект; механические напряжения; деформируемая среда; характеристика выхода; контролируемая среда; калибровки; электрическое поле.*

# THE CONTROL OF MECHANICAL STRESSES INSIDE DEFORMABLE MEDIA BY PIEZOELECTRIC TRANSDUCERS

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*Piezoelectric transducers are designed to solve a complex scientific and technical problem: control and investigation of a stressed state within deformable media. The performance of piezoelectric transducers was carried out and checked in the field measurements of mechanical stresses inside specimens of materials. The principle of operation of transducers is considered and the results of experimental studies are presented.*

*Keywords: transducer; piezoelectric effect; mechanical stresses; deformable medium; output characteristic; controlled environment; calibration; electric field.*

Introduction. The application of widely used ultrasonic methods and the traditional method of stress state control through glued strain gages, gives generalized information about the magnitude and nature of the distribution of mechanical stresses along the cross section of the monitoring object, and this is inadequate for practical purposes. The main purpose of piezoelectric transducers for controlling mechanical stresses inside deformable media is to convert measurement information about the stressed state of the object, as a rule, under the influence of interfering factors. Piezoelectric transducers realize the method of measuring mechanical stresses inside deformable media with higher reliability than strain gages, thanks to the original designs that make it possible to exclude the acoustic interaction of the converter with the controlled environment into which it is placed [1].

The relationship between the mechanical loading of piezoelectrics and the resulting electric field strength, which is used in the technique of measuring variable pressures and forces using the piezoelectric effect [2], cannot be used to determine the constant pressures, forces, since the resulting charge as a result of the piezoelectric effect rapidly flows. To eliminate this phenomenon, an auxiliary piezoelectric element is used to excite dynamic oscillations in the second piezoelectric element [3]. But transducers constructed by this method cannot be used to measure mechanical stresses inside solid continuous media, since when the piezoelectric element is excited in the converter, the latter changes its dimensions, and the environment will prevent it. In order for the piezoelectric transducer not to change its dimensions when the reverse piezoelectric effect is excited in the medium, and therefore the non-appearance of an electrical signal in the output circuit in the absence of a load, an additional piezoelectric element is applied. Moreover, in the two-layer transducer, the main, auxiliary and additional piezoelements are arranged in a column and, in addition, the main one - inside the auxiliary made in the form of a ring [1]. Based on this principle, piezoelectric converters PPMN-1, PPMN -2, PPMN-3 and PPMN -4 were developed.

**Principle of operation of piezoelectric transducers.** Schematically, such piezoelectric transducers can be represented in the form of 2 piezoelements (figure 1): the first lower is electrically excited and forces the upper to oscillate, which is excited by the measured component of the mechanical stress [3].

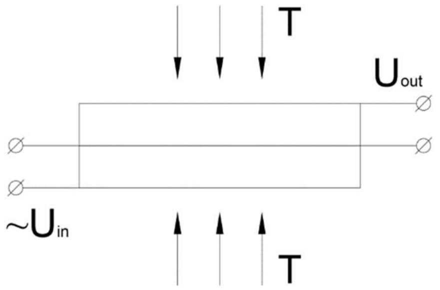

Figure 1. – Scheme of the operation of the piezoelectric transducer:
T – mechanical stress (input value of the converter)

$\sim U_{in}$ – input excitation voltage; $U_{out}$ – output voltage (transducer output);
These processes are described by the equations of the piezoelectric effect:

$$\begin{aligned} P^E &= dT + \varepsilon^T E \\ S^T &= d_t E + s^E T \end{aligned} \qquad (1)$$

Equations (1) in this case will have the form:

$$\begin{aligned} P_i &= d_{ij} \cdot T_j \\ S_j &= d_{tij} \cdot E_i \end{aligned} \qquad (2)$$

where $P^E$, $S^T$ – respectively, the polarization measured at a constant electric field E and the deformation measured at a constant mechanical stress T.

$\varepsilon$ – the dielectric constant;

*s* – elastic compliance.

Indexes *ij* – take the following values:

i=1-3; j=1-6;

$t$ – matrix transposition;

The first expression of the system of equations (2) characterizes the operation of a piezoelectric element excited by a mechanical stress. The second is the work of a piezoelectric element excited by an electric field.

Under the influence of mechanical stress on the piezoelectric element, its amplitude of dynamic oscillations changes, and hence the magnitude of the electrical voltage Uout at the output electrodes, by the change of which the magnitude of the measured mechanical stress is judged. The mechanical stress is applied to the body, where the sensitive piezoelectric element is placed [1,4]. In addition, these transducers are of parametric type transducers that require additional energy from an external source, in this case – a source of an electric alternating voltage Uv, modulated by the resistance of the piezoelectric, which varies under the influence of the measured quantity.

Transducers are devices for displaying information about the state of stress in a studied object. Any transducer (sensor) can be considered as a sequential chain of data collection, processing, storage and transmission, which is necessary to control any process.

From the physical concepts of measurement, it follows that for the transformation of the measured physical quantity, certain energy consumption are required. In the piezoelectric transducers considered here, the transmission of information is accomplished by additional expenditure of energy from an external source.

Figure 2 expresses the principle of the piezoelectric transducer of mechanical stresses (PPMN).

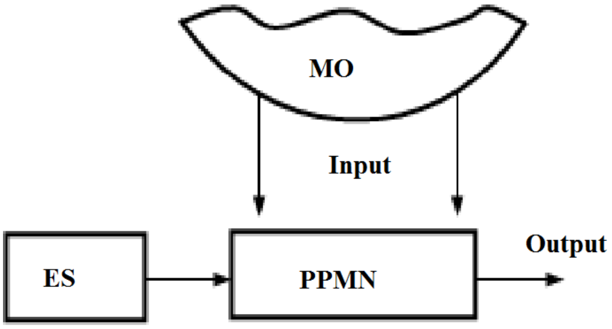

Figure 2. – Scheme explaining the operation of the PPMN:
ES – energy source; PPMN – mechanical stress of piezoelectric transducer;
MO – measurement object

To convert the measured value, the PPMN is supplied with an external energy source (ES), which is an oscillator. The energy flow received from the ES is used to transport the measurement information received from the measurement object (MO) to the output of the sensor and recorded by a voltmeter in the form of an alternating electric voltage. In this case, the resistance of the sensor changes and the external energy flux is modulated by the input value, i.e. mechanical stress from the MO. The flow of energy coming from the ES and the information flow from the MO are not only unequal, but also are in different directions.

Indeed, in order to detect, for example, an object using a photo-sensor, a certain flux of light energy must be directed from it to the ES; only the reflected part of the total stream directed to the object will be fixed by this photo-sensor.

Similarly, it is possible to treat the phenomena occurring in the PPMN. In this case, the change in mechanical stresses affects the change in the resistance of the converter, where we cannot detect these voltages until we "illuminate" our transducer, and pass through it the flow of energy from the ES.

The energy flow from the ES is much larger than the information flow from the MO, and the level of the measured mechanical stress is determined by the ratio of the intensity of the information flow from the MO to the intensity of the information flow from the ES.

Figure 3 shows the dependence of the output characteristics of one of the piezoelectric transducer samples on the energy received by the transducer from the ES, that is, on the magnitude of the exciting voltage transducer Uexc from the oscillator (see Fig. 4). At researches, as sensitive elements of gages piezo-ceramics of type TTS - 19 was used.

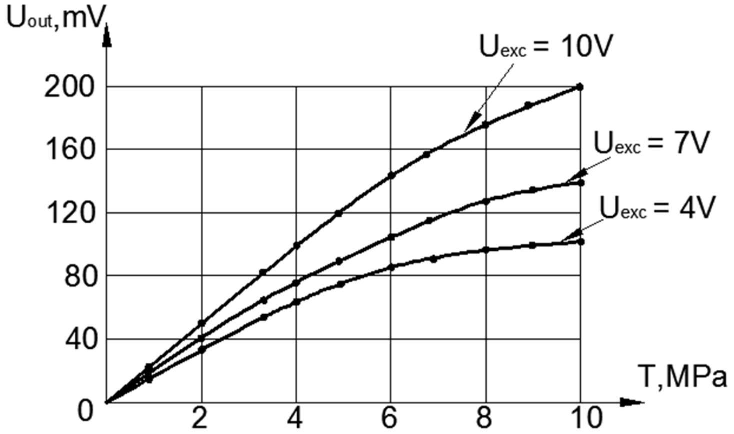

Figure 3. – Dependence of the output characteristics of the piezoelectric transducer of mechanical stresses on the value of Uv

From the analysis of the characteristics, it follows that as Uv increases, the slope (conversion coefficient) increases, i.e. sensitivity of the converter.

$$S = \frac{dU_{out}}{dT},$$

where $dU_{out}$ – change in the output value of the transducer;

$dT$ – change in the input (mechanical stress).

In other words, the more energy is consumed by the ES in comparison with the level of interference, the more this information energy can be transferred and the higher the output signal level Uout is.

Thus, the transfer of information to the PPMN is explained as follows. The carrier of the measuring information is energy. To create information on the input of the measuring channel of the mechanical stress transducer, which could then be transmitted further, it is necessary to expend energy. The higher the voltage level from the ES, that is, Uin, the more information can be transferred and the higher the output level Uout is.

Measurements must be interpreted by some data in such a way as to ensure stability and, if possible, close the conditions of the stressed state of the PPMN in calibration and in full-scale measurements. For the interpretation of the measured mechanical stresses within the controlled materials, the calibration data obtained with the uniaxial loading of the PPMN were used. The scheme for measuring the mechanical stresses is shown in figure 4.

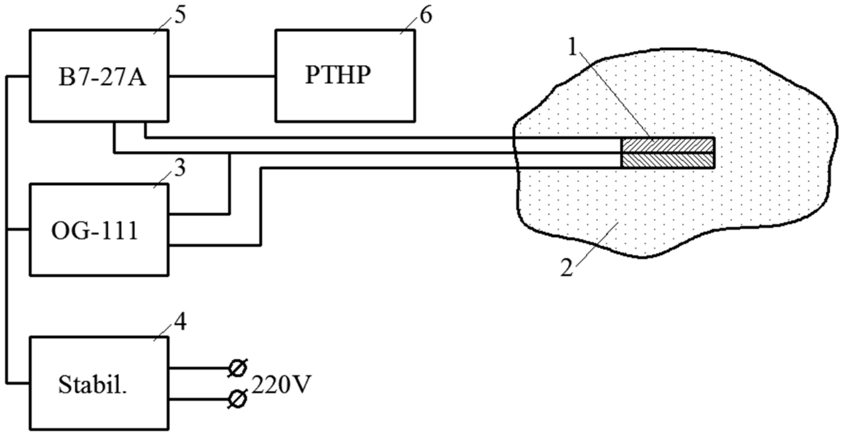

Figure 4. –Scheme of measurement of mechanical stresses:
1 – piezoelectric transducer; 2 – controlled environment; 3 – oscillation generator;
4 – voltage regulator; 5 – digital voltmeter; 6 – PTHP

Calibration of the piezoelectric transducer of mechanical stresses. The scheme of the calibration apparatus is given in [5] and is analogous to the scheme in Fig. 4; with the only difference being, that instead of the controlled environment, a mechanical loading device is used in the calibration apparatus.

The PPMNs were placed in the loading device and subjected to an uniaxial loading between the steel gaskets, which were carried out in stages at a temperature of t=20°C.

Before the start of calibration, a time delay is necessary because of the same and stable temperature conditions of the internal parts of the PPMN and the instruments. It is taken equal to 30 minutes. The power is supplied from the generator, the output signal of the PPMN - to a digital voltmeter. The power supply of the generator and voltmeter is stable. A frequency counter is used to control the oscillation frequency of the converter output signal. The calibration consists of six consecutive cycles, each of which consists in increasing the value of the load device from 0 to 100% in steps through 20% and in decreasing the value of the load by the same steps and is used for metrological studies of the PPMN, which are summarized in [6]. Dependences of the output signal on loading and unloading of the graduated PPMN are entered in a computer, coupled with a voltmeter B7-27A with the help of a developed matching device. The real function of the transformation of the PPMN will be nonlinear. The physical meaning of this non-linearity is the change in the sensitivity of the PPMN when the measured value changes. To estimate the errors in the indications of the PPMN associated with the nonlinearity of its transformation, the approximation of the actual transformation function by a straight line segment is most often used. In this case, the problem of carrying out an approximating line through a series of experimental points can be successfully solved, for example, by the method of least squares.

According to the obtained experimental data, the average values of the output value are determined under loading and unloading in Table 1. These data are then used to calculate the PPMN errors with respect to the approximating linear relationship function, which includes the actual values of the physical quantity. The equation of this approximating function in the general case has the form:

$$U = AT + B, \text{ or in the notation of a rectangular coordinate system - } У = AX + B.$$

Here coefficients A and B are functions of the input quantity and other influencing factors. From the point of view of the effect on the resulting measurement accuracy, A – represents the sensitivity of the sensor sensitivity, B – the error of zero, U – the electrical voltage (output value of the PPMN), T – the mechanical stress (input value). In other words, from the experimental values of the input and output values, the sensitivity of the sensor A is calculated, which is the tangent of the slope of the approximating line to the abscissa axis and a constant value of B, which is the ordinate of the point of intersection of this line with the coordinate axis.

Further, taking into account normative documents [6], the following parameters of sensor error are determined:

$\Delta$c – systematic component;

$\tilde{\sigma}$ - root-mean-square deviation of the random component;

b – variation of the output signal;

$\delta$ - relative error.

Table 1. – Measuring and calculation data obtained with the calibration of piezoelectric transducers by uniaxial loading

| Load device readings, MPa | Output voltage of the converters (arithmetic mean values of six measurements), V | | | | Calibration mode U (f, Hz) | Angular coefficient (sensitivity) SR, mV / MPa | Transducer type |
|---|---|---|---|---|---|---|---|
| | Loading | | Unloading | | | | |
| | experiment | calculation | experiment | calculation | | | |
| 0 | 0,998 | 0,998 | 0,990 | 0,999 | 10; (800) | 8 | PPMN-2 |
| 2,15 | 1,017 | 1,013 | 1,026 | 1,023 | | | |
| 4,30 | 1,038 | 1,028 | 1,045 | 1,036 | | | |
| 6,45 | 1,054 | 1,044 | 1,060 | 1,05 | | | |
| 8,0 | 1,062 | 1,059 | 1,071 | 1,063 | | | |
| 0 | 1,995 | 1,993 | 1,990 | 1,986 | 10; (800) | 11 | PPMN-4 |
| 2,15 | 1,025 | 1,021 | 1,023 | 1,020 | | | |
| 4,30 | 1,050 | 1,042 | 1,051 | 1,049 | | | |
| 6,45 | 1,068 | 1,064 | 1,060 | 1,059 | | | |
| 8,0 | 1,086 | 1,080 | 1,081 | 1,078 | | | |

Checking the performance of piezoelectric transducers for in-situ measurements of mechanical stresses within specimens of materials

The control of the stress state along the cross section of the object, that is, inside the materials, must be carried out by direct measurement of mechanical stresses by special transducers, which provide accuracy sufficient for practical purposes [6].

The solution of such problems is greatly simplified when there are experimental data obtained as a result of static testing of samples of materials.

The stress transducer was pressed into the polymer material by means of a heating device. After the shrinkage of polyethylene within 24 hours and measurement of internal stresses, it was subjected to mechanical loading, and more about this is to be stated below. When the sample cools as a result of shrinkage, for example in polyethylene, due to the uneven cooling and due to the linear expansion coefficient of the transducer and medium, the internal stresses T appear in the latter. The magnitude of these stresses is determined experimentally by comparing the transducer's readings with the calibration of the transducer's readings determined after shrinkage. Tests were subjected to 2 grades of composite compositions (Table 2).

Table 2. – Properties of materials

| Notation of composition designation | A | B |
|---|---|---|
| Composition | Polyethylene of high pressure<br>(PTHP) – 85%<br>Fiberglass<br>(FG) – 10%<br>Talc – 5% | PTHP – 90%<br>FG – 10% |
| Density, g/cm$^3$ | 1,0378 | 1,0387 |

The results of testing transducers in compositions A and B, the physical and mechanical properties of which are given in Table 2, are given in figure 5 and 6.

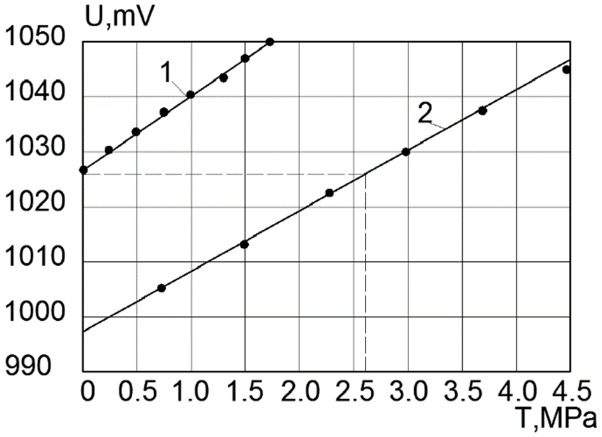

Figure 5. – Readings of the piezoelectric transducer PPMN-2 under uniaxial loading:
1 – in material A; 2 – between steel gaskets (calibration characteristic, load)

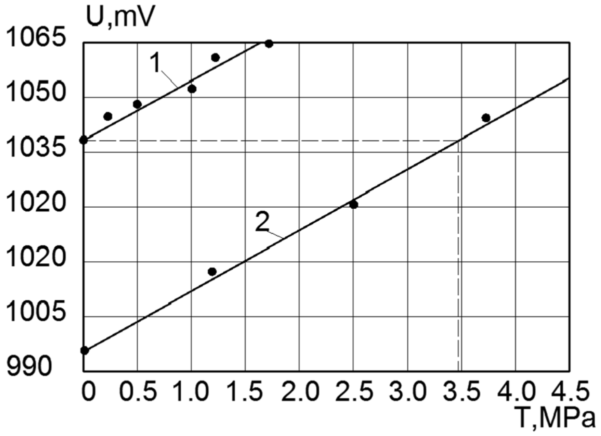

Figure 6. – Readings of piezoelectric transducer PPMN-4 under uniaxial loading:
1 – in the material B; 2 – between steel gaskets (calibration characteristic, load)

To assess the impact of the interaction of the PPMN with composite materials, as well as measurement of internal stresses in the samples of these materials, the same measuring instruments as for the calibration were used. The measurement scheme is shown in Fig. 4. To measure the PPN, the diameter and height of the sample of the material of a cylindrical shape were pressed into the sample, respectively, 50 mm and 20 mm, made up of disks, figure 7. For this purpose, a hole, equal to the diameter of the converter, was drilled in one of the discs. On the surface of the disk, grooves were cut out, in which the converter's terminals were laid and fixed.

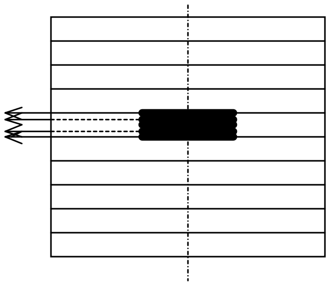

Figure 7. – Diagram showing a prism of disks

On the transducer installed in the disk, we placed more polymer discs from below and above. The formed cylinder of 10 disks was fastened (fixed) with a heated electric soldering iron and was wrapped with thin and dense paper along the entire generatrix to prevent adhesion to the walls of the heating device when the polymer melted. To press the transducers into the samples the of the studied materials, to measure internal stresses in them, a heating device was made, Fig. 8.

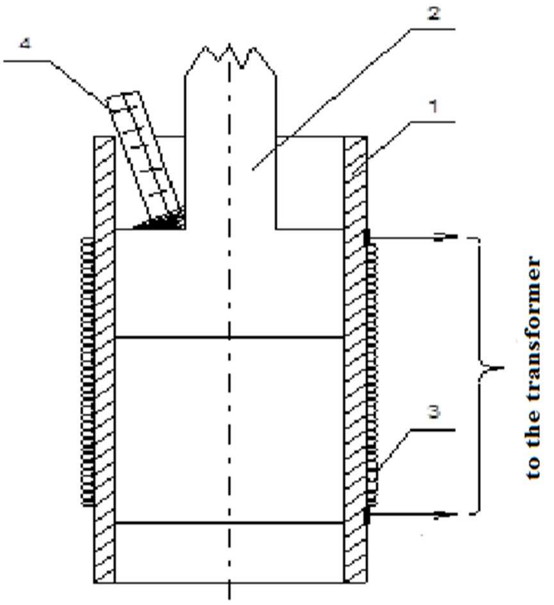

Figure 8. – Diagram showing the heating device

The device is a matrix in the form of a metal hollow cylinder 1 with external and internal diameters, respectively, 61 mm and 51 mm, a height of 150 mm and a punch 2. On the outside of the matrix, an electrical spiral 3 is wound through the insulating liner to heat the cylinder with an electric current controlled by laboratory transformer.

The inner surface of the matrix and the outer surface of the punch adjoining it must be ground and densely joined to each other. The temperature is monitored by a mercury thermometer 4 with a scale up to 300°C, which is placed in the gap formed by the handle of the punch and the inner surface of the cylinder, Fig. 6. The thermometer was attached to the surface by Wood's alloy.

Due to the experimentally selected heating regimes (temperature, heating time and pressure, respectively, 175°C, 30 min and 0.3 MPa), a sample with a measuring PPMN placed in the cylinder after melting and solidification had a continuous structure without shells. As a result, the transducer, after shrinkage of the polymer for 24 hours, was densely pressed. Then it was connected to the measuring circuit in Fig. 4, after which the readings of the digital voltmeter B7-27 were taken. When the sample cools as a result of the shrinkage of the polymer, due to uneven cooling and the linear expansion coefficient of PPN and the medium, internal stresses T appear in the latter.

According to the calibration characteristic, the internal stresses arising in the polymer sample were determined. For example, in Fig. 5, the voltmeter reads 1026 mV, taken from the pressurized controlled medium of PPMN, which corresponds to 2.65 MPa. This is the internal tension in this environment.

The loading of the PPMN in the sample of the material monitored by it was carried out in order to determine the distortions of the controlled stresses introduced by the PPMN, as by foreign inclusion. The magnitude of the distortion coefficient depends on the ratio of the moduli of elasticity of the medium and the sensor [5].

The requirements for PPMN are formed depending on the type of environment into which it is placed: it is desirable that the modulus of elasticity is the same as the modulus of elasticity of the environment. However, if the modulus of elasticity of the medium changes under the influence of mechanical stresses, the accuracy of the sensor will be less if its rigidity is maintained approximately the same as the rigidity of the medium.

To this end, piezoelectric transducers of static mechanical stresses of the type PPMN have been developed, the elastic moduli of which are in a wide range ($5 \cdot 10^3 \div 10^5$ MPa). This makes it possible to use a specific modification of the PPMN depending on the rigidity of the monitored object, in order to increase the accuracy of the measurements, since it is known that the closer the controlled medium and the PPMN placed in it are in terms of rigidity, the more accurate the measurement is [5].

The output characteristics of the transducer and the transducer placed inside the polymer sample under loading differ, firstly, by the steepness by the amount of the distortion factor of the stresses caused by the transducer as a foreign inclusion, and secondly by the displacement of zero (the beginning of the characteristic) by an amount internal stresses, Fig. 5.6

Conclusions. To interpret the mechanical stresses inside the controlled materials and products from them, measured by the developed piezoelectric transducers, a calibration characteristic obtained by uniaxial mechanical loading was used.

Distortions of measured mechanical stresses by piezoelectric transducers placed inside the medium, like foreign inclusions, are accounted for by applying a particular type of piezoelectric converter, depending on the rigidity of the controlled medium.

A further line of research will be the use of such sensors in building materials and structures [7-9], and also in order to intensify the introduction of BIM-technologies in the Republic of Belarus.

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