ROCKET-SPACE DEVICE ENGINEERING AND INFORMATION SYSTEMS
Vol. 3, Iss. 1, 2016, pp. 66–72

Correction of Temperature Error of Pressure Piezoelectric Sensors for Space Technology Products

V.P. Malanin[1], V.V. Kikot, P.N. Efimov

[1]candidate of engineering science
Joint-Stock Company "Research institute of physical measurements", Russia
e-mail: ait@pnzgu.ru, inbox@post.su, nik2@niifi.ru

Abstract. The article presents the questions of correction of temperature error of piezoelectric pressure sensors in conditions of transient temperature and thermal shock. It is noted that when the piezoelectric pressure sensor is operating in thermal shock conditions, it is important to measure the main parameter by means of the piezoelectric sensor: the pressure and piezoelectric element temperature at a single point of space and at the same time to eliminate the influence of the temperature gradient. That makes difficult to use additional sensors to measure the temperature of the actuating medium. It is proposed to use the impedance parameters of working and vibrocompensation piezoelectric elements as information source about the temperature of piezoelectric elements. The scheme of secondary transmitter of output signals of working and vibrocompensation piezoelectric elements is presented; its description and algorithm for obtaining the correction signals are described. The results showed that the change of the conversion efficiency of the pressure piezoelectric sensor of the piezoelectric elements form the PZT-83G piezoelectric material in the range of - 180 to + 200 °C is approximately 35%. Moreover, time dependence of output signals from the working and vibrocompensation piezoelectric elements of the pressure piezoelectric sensor when exposed by thermal shock of liquid nitrogen is presented. It is shown that using the proposed correction method of measurement errors from the transient temperature of the actuating medium can reduce measurement error of dynamic pressure from the thermal shock.

Keywords: pressure sensors, piezoelectric element, temperature error, membrane, equivalent circuit, impedance, conversion efficiency

Sensors are the basis of automatic control systems for space applications. Sensors perceive not only the data on the measured value, but also the impact of wide range of influencing factors that emerge during the operation in the so-called harsh environments. The sensor equipment, used for this purpose, is exposed to an extremely concentrated and complex effect of destabilizing factors, such as change of pressure, high levels of vibration and shock, acoustic noise, transient temperatures of the actuating medium, thermal shocks. The influence of the quick-changing and acoustic pressures of transient cryogenic temperatures, which affect the sensing elements of the primary transducers of piezoelectric sensors, on the metrological characteristics of the sensors is one of the most important factors that determine whether the use of these sensors is possible in each specific case.

Development and improvement of methods of temperature error correction in piezoelectric sensors are the tasks of many aviation and space technology development organizations, since a distinctive feature of the sensor equipment usage in these fields is the impact of transient temperature on the sensors. The initial conversion of the dynamic pressure under powerful and quick-changing temperature effects in ranges from -253 to +300° c causes temperature transients in sensors and, as a consequence, increased measurement errors of dynamic input non-electrical values during the transients. The transients in piezoelectric sensors under a thermal shock can last from seconds to tens of minutes, depending on the specific characteristics of the individual sensor units. Ensuring stability and accuracy of measurement of dynamic pressures during that time is a serious and urgent problem. To date, two well-known techniques of temperature sensor error correction have formed. The first technique is based on reducing the power of the effecting destabilizing factor, while the second one suggests reducing the sensitivity of the sensor's metrological characteristics to temperature.

References [1-3] describe the search for the balance between the universality of use, reliability of the developed sensors and their metrological characteristics. The pursuit of universality, for example, imposes restrictions on the metrological characteristics, resulting in complication of sensors operation because of the necessity of additional structural elements (leading piping to reduce the temperature of the actuating medium, adapters, structural units with intermediate temperature-controlled environments, through which the pressure is sensed), as well as the need to perform additional configuration of a sensor for the desired measuring range of dynamic pressures, etc. The distinction of this approach lies not in designing sensors for systems, but, on the contrary, in designing systems for sensors. If, however, the main objective is to improve the reliability and metrological characteristics of sensors, then, for example, for different dynamic pressure measuring points in a device with controlled parameters of the actuating medium it is possible to use sensors of various designs and conversion methods to achieve the best metrological characteristics and high reliability. Various challenges of designing the sensors and solutions to them have generated a pool of constructive scientific and technical designs, that are currently in use.

It is also important to take into account the mutual influence of constructive elements, with their physical and electrical parameters changing as the temperature of the actuating medium changes. The thermoelastic displacement in the body of a sensor and it's connected elements, the differences in the dimension changes due to different linear extension thermal coefficients of the materials of the sensor's elements, the tension and deformations of the membrane material, pyroelectric effects in the piezoelectric element of the sensor are just a few consequences of changes in the temperature of the actuating medium. The commonly known constructive designs for reducing the impact of temperature on the dynamic pressure measurement accuracy are:

1) increasing the mass of a sensor to compensate for the impact of the thermal shock, the downside of this solution is the increased mass of the sensor and decreased operation speed;

2) coating the sensor membrane with a layer of silicone rubber, ceramics or installation of asbestos cloth soaked in low viscosity oil in front of the membrane , which affects the sensitivity of the sensor;

3) the use of various modifications of membranes.

For example, when measuring high pressures, it is possible to employ a membrane in the form of a thin plate, that is manufactured together with the sensor casing, but such a design usually requires either a threadless connection at the sensor installation point, or an additional external installation casing in order to prevent the indirect influence of tightening on the metrological characteristics of the sensor. The sensors exposed to thermal shocks feature a membrane in the form of a thin plate, that connects to the sensor casing by welding, but welding does not provide the sufficient reliability for the

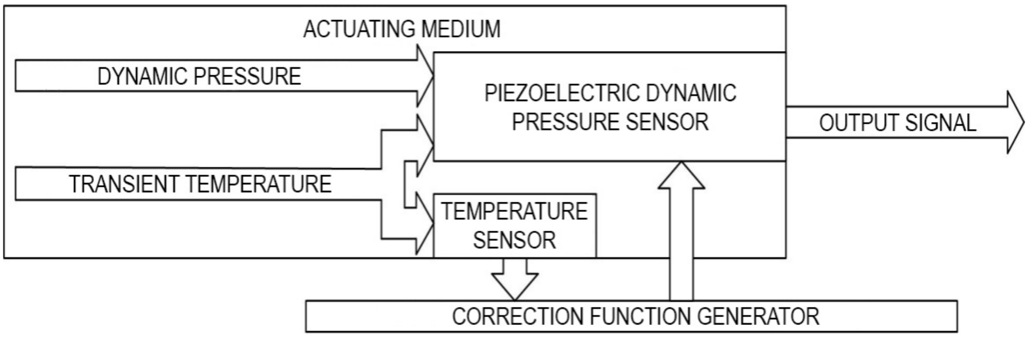

Fig. 1. Structure of a piezoelectric dynamic pressure sensor with a temperature sensor

prolonged use of the sensor in some aggressive environments. To increase the service life of the sensors when measuring high pressures at the temperatures of up to 800 °, membranes in the form of pistons are employed, but another force-transferring element of the construction reduces the sensitivity of the sensor.

One of the design options for reducing the impact of temperature on dynamic pressure sensors is the temperature control that can be implemented, for example, by introducing the means of forced cooling into the sensor design using channels in the casing of the sensor for coolant passage. Temperature control provides the best thermal stability of the piezoelectric sensors, but the small operating temperature range, relatively large dimensions and high power consumption limit the use of such sensors.

Temperature compensation is also a widely used method of circuit temperature error correction. In contrast to temperature control, when thermal compensation is employed, the generated compensatory effect is applied to the output signal of the sensor under the impact of temperature as a destabilizing factor, which results in changes to the output signal, caused by temperature changes, converging to zero. The typical structure of piezoelectric sensor for dynamic pressures with temperature compensation employed is presented on Figures 1 and 2.

When measuring dynamic pressure using a temperature measurement channel for the temperature of the actuating medium, the temperature sensor can be installed separately from the dynamic pressure sensor. When the temperature sensor is installed at a different location, the temperature differences at the temperature measurement point and the pressure measurement point as well as the different rate of temperature change of the sensing elements of the pressure sensor and the temperature sensor under thermal shock impact the accuracy of the pressure measurements. Performance of temperature sensors is determined by their response rate, which, depending on the model, varies from 0.05 to 20 seconds, whereas the duration of the transients in dynamic pressure sensors, including temperature changes of their piezoelements, as mentioned above, can reach tens of minutes. This results in the decrease in the precision of the dynamic pressure measurement, more complicated definition and implementation of the corrective function, as well as the increase in the amount of work required during the initial tune-up of the system before operation.

Application of circuit techniques for reducing the effects of temperature impacts is devoid of the weaknesses of constructive and technological methods. Development of nano- and micro-electromechanical technologies, miniaturization of sensing elements, as well as the electrical circuits of secondary transducers, make it possible to combine circuit and structural design methods for the development of sensors, allowing the creation of fundamentally new designs of sensors and control systems. This is facilitated by the emergence of new piezoelectric materials, such as langatate and langasite, which are able to withstand severe thermal shock. For example, it has become possible to locate both dynamic pressure and temperature sensors and, when necessary, the circuits of secondary transducers a in a single casing. This also improves the weight dimension characteristics of the measuring systems in which these sensors are included. An advantage of this arrangement of the temperature sensor is measuring temperature and dynamic pressure at a single point without spatial separation of the channels to measure them. The accuracy of pressure measurement in this case is indirectly affected by the differences in the physical characteristics of materials of the elements versus the temperature.

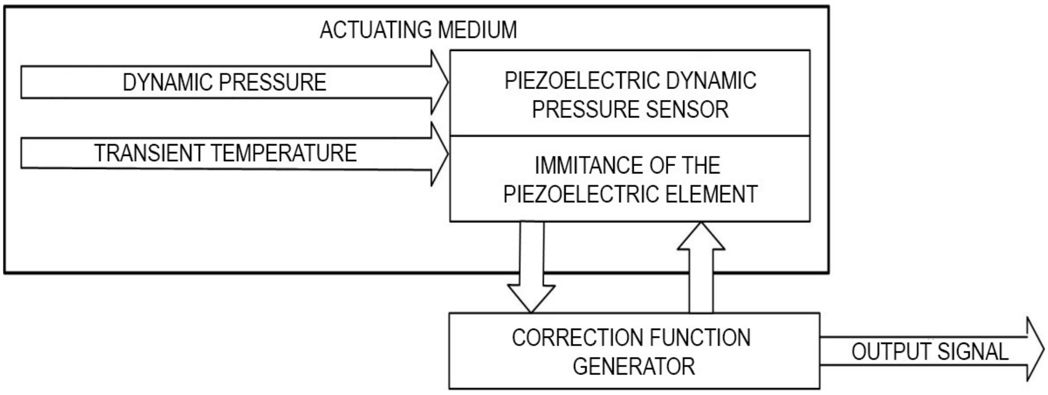

Fig. 2. Structure of a piezoelectric dynamic pressure sensor without a temperature sensor, with the immitance of the piezoelectric element used for temperature measurements

Another promising method for correcting the temperature-induced error in dynamic pressure measurement is using the parameters of piezoelectric elements for measuring temperature - the impedance analysis of piezoelectric elements. For instance, the dependence of the electrical capacity of the piezoelectric element of dynamic pressure sensor on temperature is used for generating the temperature error correction signal. Specifically, the dependence of voltage drop amplitude of the high-frequency current signal on the complex resistance of the piezoelectric element, which is, in turn, expressly dependent on temperature, can be used for temperature measurement. During the sensor's operation the instantaneous measured values indicate the temperature and the correction value for its sensitivity changed by temperature. The practical implementation of said design is the temperature error correction device developed by the authors. Its block diagram is shown in Fig. 3. This method of correction, based on impedance analysis of the piezoelectric element, has a number of advantages:

a) reduced weight dimension characteristics of the sensor due to use of a single primary measurement transducer for dynamic pressure and temperature measurement;

b) increased accuracy of measurement due to no spatial separation of the measuring points of dynamic pressure and temperature within the monitored object;

c) simplified circuitry of the secondary transducers, forming the correction signal, due to identical physical and electrical parameters of the sensor elements for measuring dynamic pressure and temperature;

g) improved metrological characteristics and performance due to reduced response time of the sensor;

d) possibility to upgrade existing designs that include piezoelectric dynamic pressure sensors.

Application of the impedance analysis method in conjunction with other circuitry and structural methods, aimed at improving the accuracy of dynamic pressure measurement and correction of temperature errors, will allow the newly designed sensors meet the ever-increasing requirements for reliability of control systems.

The main circuit signal processing method for correction of errors caused by the influence of destabilizing factors is implemented in the secondary transducer. It involves sending the data on the affecting destabilizing factor directly to the primary transducer and computation of the output correction signal using the sensors microcontroller. When piezoelectric sensors operate under a thermal shock, in order to eliminate the influence of a temperature gradient, it is important to measure the main parameter, pressure, and the temperature, affecting the piezoelectric element at a single point in space and at the same time, making it difficult to use additional sensors with spacial and temporal separation of the measuring channels for measuring the temperature of the actuating medium.

Authors consider a piezoelectric element model represented in equivalent circuit form, which consists of a power supply, which has internal resistance, and the complex resistance of the piezoelectric element. Complex resistance of a piezoelectric element is composed of the piezoelectric element leakage resistance and the capacity reactance of the piezoelectric element. For the piezoelectric element temperature measurement it is proposed to use the dependence of voltage drop amplitude of the high-frequency harmonic current of the current

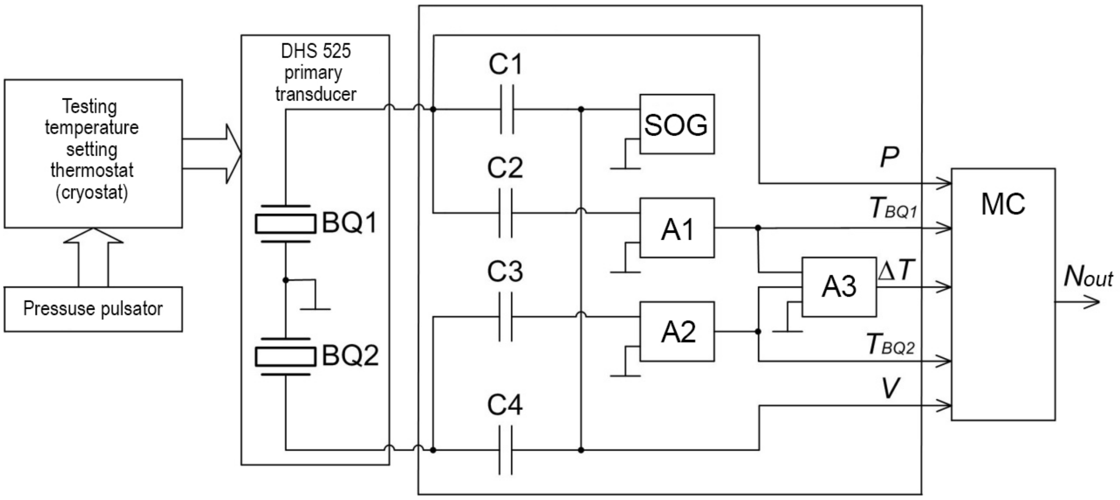

Fig. 3. Measurement diagram.

signal of the current source on the complex resistance of the piezoelectric element. An experiment to study the temperature characteristics of the actual and the compensating sections of the piezoceramic module PM 7-02V produced of material 83g-PZT (piezoelectric element) sensing element (SE) pressure sensor DHS 525 (sensor) was carried out using the measuring circuit shown in Figure 2, where *BQ1* and *BQ2* are the actual and the compensating sections of the piezoelectric element, respectively, *C1* - *C4* are the capacitors used to separate the pressure and temperature measurement channels.

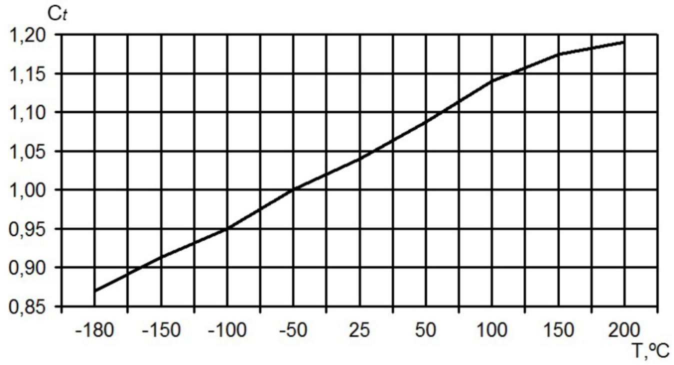

Fig. 4. The dependence of temperature effect coefficient *C*t on temperature T.

Pressure pulsator is used to set the pressure pulsations for the determination of the coefficient of the effect of temperature *K*t on the sensor's conversion efficiency *K*. The sinusoidal oscillation generator *SOG* feeds a sinusoidal currency signal at a frequency of 1 MHz and a crest voltage of 12V to the actual *BQ1* and the compensating *BQ2* sections of the piezoelectric element. Under the influence of temperature changes in sections *BQ1* and *BQ2* of the piezoelectric element of the sensor SE, which are set by a thermostat (cryostat), the amplitude of the voltage drop on the impedance of the *BQ1* and *BQ2* sections the piezoelectric element change their values. The signal of the dynamic pressure Δ*P*, picked up from the actual electrode section *BQ1*, in which the temperature impact *T* and vibration *V* is not compensated, is fed to the first input of the microcontroller MC. Vibration signal *V* picked up from the electrodes on the vibrocompensated section *BQ2*, in which the temperature impact *T* is not compensated, is fed to the fifth input of the microcontroller MC. Temperature signals T_{BQ1} and T_{BQ2} picked up from sections *BQ1* and *BQ2* of the piezoelectric element are amplified by the first A1 and the second A2 high-frequency amplifiers for the voltage drop across the impedance of piezoelectric elements *BQ1* and *BQ2* and fed to the second and fourth inputs of the microcontroller MC, respectively. Also, the signals T_{BQ1} and T_{BQ2} are utilized to produce with a using a high-frequency amplifier the voltage drop difference for the production of ultrasonic signal ΔT of the temperature difference between the actual *BQ1* and the vibrocompensating *BQ2* sections of the piezoelectric element when exposed to thermal shock. Signal ΔT is fed to the third input of the microcontroller MC The microcontroller MC performs the correction of the dynamic signal pressure ΔP and vibration *V*, impacted by the changes in temperature *T* of the actuating medium, using the signals of the dynamic pressure ΔP, temperature *T*, vibration *V*, temperature difference in the

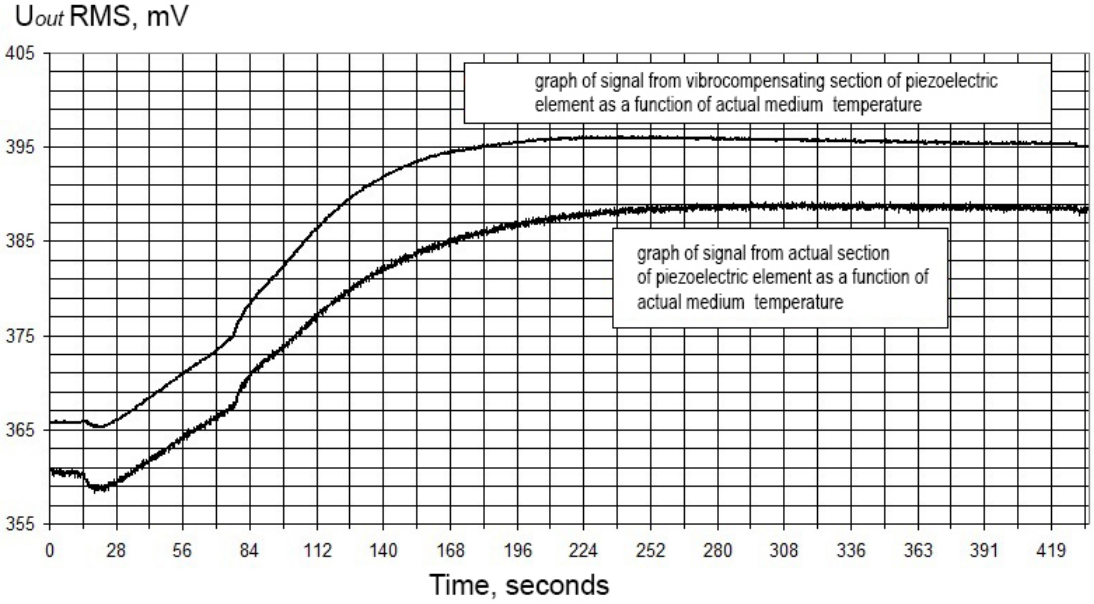

Fig. 5. The dependence of the output signals of the actual*BQ1* and compensating *BQ2* sections of the piezoelectric element on temperature;

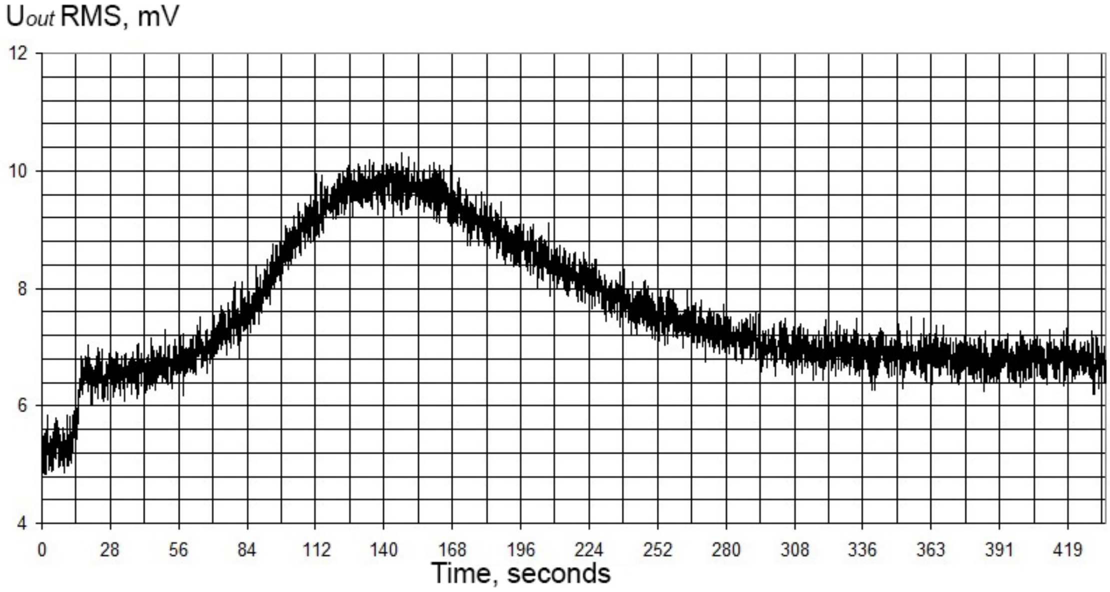

Fig. 6. The dependence of the difference in output signals from the piezoelectric element sections on temperature.

sections of the piezoelectric element ΔT. The microcontroller MC outputs a digital signal *N*out with data on the dynamic pressure Δ*P* and temperature *T* of the actuating medium as well as vibration *V*, which affects the sensor's SE. Figure 3 shows the attained dependence of coefficient C_T of the effect of the temperature of the actuating medium in the temperature range from -180 to +200 ° C for the conversion coefficient C_c of the DHS 525 sensor›s SE. Figure 4 shows that the deviations of the conversion factor of the sensor›s SE, resulting from the effect of temperature gradient, are approximately 35% throughout the range of operating temperatures.

The time dependence of the output signals of sections of the piezoelectric element SE on the temperature gradient of the actuating medium from +23 to -196°C, was also deduced and shown in Figure 5.

Also the time dependence of the difference between the output signals of the piezoelectric element sections was determined, which is shown in Figure 6.

As can be seen from Figures 4 and 5, the change rates of the output signals of the piezoelectric element sections affected by temperature gradient are different for a period of time. This happens because of the uneven heating of the sensor's SE during the temperature change and leads to a measurement error in the output signal of the sensor's SE. This error is compensated by using the measurement circuit shown in Fig. 3.

The practical implementation of the correction of temperature error in piezoelectric sensors based on the method of impedance analysis of the piezoelectric element will improve measurement accuracy of the mass-produced, as well as the newly designed piezoelectric dynamic pressure sensors, and will expand the operating temperature range.

References

1. *Proektirovanie datchikov dlya izmereniya mekhanicheskikh velichin* [Sensors designing for mechanical quantities measurement]. Moscow, Mashinostroenie, 1979, 482 p. Ed by Osadchiy E.P. (in Russian)
2. *Datchiki. Preobrazovateli. Sistemy. Katalog OAO "NIIFI"* [Sensors. Converters. Systems. The catalogue of JSC "Research institute of physical measurements"]. Penza, Penzenskaya Pravda, 2011, pp. 70-98. (in Russian)
3. Malanin V.P., Shamrakov A.L., Kikot V.V. Ustroystvo korrektsii temperaturnoy pogreshnosti p'ezoelektricheskikh datchikov davleniya [The correction device temperature error piezoelectric pressure sensors]. *Izmerenie. Monitoring. Upravle-nie. Kontrol'* [Measurement. Monitoring. Management. Control]. Penza, PGU, 2014, №3 (9), pp. 71-76. (in Russian)