Metrol. Meas. Syst., Vol. 31 (2024) No. 4, pp. 657–671
DOI: 10.24425/mms.2024.150293

POLSKA AKADEMIA NAUK

METROLOGY AND MEASUREMENT SYSTEMS
Index 330930, ISSN 0860-8229
www.metrology.wat.edu.pl

DEVICE FOR DYNAMIC CALIBRATION OF PRESSURE SENSORS

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Abstract

Modern devices for dynamic calibration of pressure sensors (shock tubes, power simulators of pressure impulse, *etc.*) have a number of drawbacks stemming from the principles of creating a test impact. Besides, the problem of rational choice of the method of calibrating pressure sensors depending on the dynamic parameters of the sensor and the required test accuracy has not been solved for modern test systems. The paper presents a solution to the problem of correlation between the test parameters, dynamic parameters of the pressure sensor and test accuracy. The obtained analytical dependencies of such a relationship make it possible to reasonably select or develop a method for studying the dynamic characteristics of sensors. Based on theoretical studies, the principle of creating a test impact has been proposed, and a method and device for implementing dynamic calibration of pressure sensors have been devised. The developed device allows the transient response of the sensor to be obtained, as well as setting the decay time of its natural vibration. Based on the transient response, other dynamic characteristics of the sensor, namely the impulse transient and frequency response, can be calculated.

Keywords: dynamic calibration device, pressure sensors, dynamic characteristics.

1. Introduction

High-precision sensors with high metrological reliability for measuring various non-stationary physical quantities, including non-stationary pressure sensors [1–3], are critically needed in high-tech industries (aerospace and arms industry, testing facilities, *etc.*) or scientific research.

Piezoresistive sensors constitute a significant share of pressure sensors in modern measurement systems as they offer several advantages for measuring the parameters of fast-changing non-stationary processes. Besides, the pressure measurement process itself must be carried out in real time, and using non-stationary pressure measurement methods in real time requires accurate knowledge of the dynamic characteristics of sensors [4, 5]. Therefore, the development of more effective methods and devices for studying the dynamic characteristics of pressure sensors is an urgent task.

Article history: received February 22, 2024; revised July 3, 2024; accepted July 10, 2024; available online September 10, 2024.

2. Analysis of the subject area and setting goals of the research

Special attention in the field of non-stationary pressure measurement is paid to the improvement of methods and devices for testing sensors, which emphasizes the importance of the problem. Advanced achievements of scientists are regularly published in leading scientific and technical journals.

Studies of dynamic characteristics of non-stationary pressure sensors are carried out with input signals in the form of pressure surge or short pressure impulse. These test signals are obtained in such devices as shock tubes, power simulators of pressure impulses, various inertial piston devices, and valve or membrane pneumatic or hydraulic systems [6, 7].

The research [8] describes a method of calibrating pressure sensors using a shock tube and a method of correcting test results due to vibration processes in the device. The proposed method is based on the simultaneous measurements of the vibration acceleration of the pressure sensor during its calibration in a shock tube. The presented studies show that testing of pressure sensors in shock tubes is a rather complex procedure due to vibration processes in the body of a shock tube, which leads to uncertainty in the test results. The complexity of the test procedure and the device itself entails the high cost of sensor calibration. Despite a detailed description of the test features, the authors do not address the problem of the relationship between the parameters of the test impact, dynamic parameters of the sensor and the accuracy of the tests.

It is noted in [9] that testing with a shock tube has its advantage: a sharp increase in the test signal edge. However, the authors point out that establishing the exact parameters of the test impact is a difficult task since the test medium is treated in the test simulation as an ideal gas, which is an approximation. In general, the authors emphasize that shock tubes are expensive and complex tools. To reduce the cost, they suggest making the tube body of plastic. The authors do not propose any other concepts and do not consider the problem of the relationship between the parameters of the test impact, the dynamic parameters of the sensor, and the accuracy of the tests.

The research [10] discusses some principles of dynamic pressure measurements and provides an overview of the dynamic calibration of piezoelectric pressure sensors in a shock tube. However, the authors do not present any new calibration concepts, only the course of the research is outlined, which is similar to other known shock tube tests. This method, therefore, has all the disadvantages that were described in the previous paper, namely, the accuracy of the test results is affected by the vibration of the shock tube body, changes in the temperature of the medium due to a sharp change in pressure and reflected waves in the tube. Besides, the researchers do not address the problem of the relationship between the sensor parameters, test impact parameters, and the desired test accuracy.

The paper [11] notes the relevance of improving the test procedure for dynamic pressure sensors and presents the design of a device for their calibration. The principle of operation of the device is to create a test impact on the sensor with a pressure impulse. This effect is created in a cylinder with a liquid by the fall of a load onto the piston of the cylinder. Although this method manages to create a fairly short test pressure impulse, it also has several fundamental problems. Firstly, to know accurately the parameters of the test impulse, it is necessary to establish the force of the load on the piston, and to do this, it is necessary to measure the acceleration of the load upon impact. This complicates the calibration procedure and reduces its accuracy. Secondly, it should be noted that additional waves propagate in the liquid from elastic vibrations of the piston due to the impact, which also reduces the accuracy of calibration. Besides, the work does not solve the problem of the correlation of sensor parameters and a specified degree of test accuracy with the parameters of the test impulse.

*Metrol. Meas. Syst.,*Vol. 31 (2024), No. 4, pp. 657–671
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A method similar to the previous one is proposed in the research [12]. To obtain a test pressure impulse, the fall of the load onto the piston is used, which sharply increases the pressure in the hydraulic medium. This method has the same disadvantages and problems as the previous one. The paper describes the implementation of the method itself, but the authors do not address the problem of the relationship between the test accuracy and test impact parameters.

The paper [13] presents a method of dynamic calibration for the dynamic sensitivity coefficient of the pressure sensor in a free field of liquid using the Hopkinson bar. The essence of the method is to create an elastic wave in a liquid medium using shock deformation of the Hopkinson bar. The signal of the Hopkinson bar deformation and the output signal of the sensor are compared based on Hopkinson's experimental technique.

In terms of the physics of the processes, this is a rather complex method, if only because an elastic wave in the Hopkinson bar is created by the impact on it. The problem of the identity of repeated experiments arises here among other things. This method, however, has its advantages for the calibration of sensors in a free field of a liquid. However, the authors do not consider the problem of correlation between the test accuracy, dynamic characteristics of the sensor, and test impact parameters.

The paper [14] describes the dynamic calibration of pressure transducers and accelerometers, carried out by the pressure impulse created in the medium by the fall of the load on the piston. The authors emphasize the influence of the test signal model, as well as the resolution and sampling rate of the data acquisition boards on the accuracy of determining the sensitivity of the transducer. However, the authors do not provide any specific numerical data or theoretical justification for the relationship between the test accuracy, dynamic characteristics of the sensor, and test signal parameters.

The paper [15] also notes the relevance of improving the test procedure for dynamic pressure sensors and presents the design of a device for their calibration. In the study, some principles of pressure measurement are considered and a method of dynamic calibration of pressure sensors is presented. Besides, the researchers do not address the problem of the relationship between the sensor parameters, test impact parameters, and the desired test accuracy.

A generalized conclusion based on the review of the literature is that the problem of correlation between the test impact parameters, dynamic parameters of the sensor and accuracy of tests remains unexplored. Besides, the main methods and corresponding devices (shock tube or falling body) have an area of uncertainty in test results. Such uncertainty stems from the complexity of the process of creating a test signal, as well as secondary physical phenomena: vibrations of the tube body and piston, changes in the temperature of the medium.

The adequacy of sensor test results will be higher if the test impact is closer to the ideal pressure surge or short impulse. Substituting the ideal test impact for the real signal will lead to a test error, which will be methodical in its essence. As can be seen from the existing research, creating test signals that are as close to ideal as possible is difficult and expensive. Therefore, an urgent task arises: to determine how close the test signal should be to the ideal one so that the test result is acceptable in terms of accuracy and the tests are economically justified. This problem can be solved by studying the correlation between the parameters of the test signal, the dynamic characteristics of the tested sensor and the accuracy of the test results determined by the conditions of further application of the sensor.

That is why the goal of the study is to develop a device for dynamic calibration of pressure sensors based on the solution to the problem of correlation between the test accuracy, dynamic characteristics of the sensor, and test signal parameters.

3. Theoretical aspects. Study of correlation between the test signal parameters, dynamic parameters of the sensor, and methodical test error

The existing methods and devices for dynamic testing of pressure sensors differ in the type of dynamic characteristics obtained, the accuracy of determining the characteristics, and the cost of the test procedure.

The most common pressure surge test signals generated in the existing devices have different leading-edge times. It is obvious that the steeper the leading edge of the test signal is, the more similar it is to the ideal one, and therefore the adequacy of the received output signal is higher. However, creating a faster effect is more difficult and expensive. Thus, during the dynamic test of pressure sensors, there is a problem of optimal selection of the necessary parameters of the test impact, and therefore, of the test method in general.

An ideal pressure surge (Fig. 1a) is described by the function:

$$p(t) = p_0 = \text{const} \quad \text{at} \quad t \geq 0. \tag{1}$$

The leading edge (Fig. 1b) coincides with the half-cycle of the cosine wave in a real pressure surge [16–22], i.e.:

for $0 \leq t \leq t_1$:

$$p(t) = \frac{p_0}{2}(1 - \cos \eta t), \tag{2}$$

and for $t_1 \leq t \leq t_2$:

$$p(t) = p_0 = \text{const}, \tag{3}$$

where $\eta = \pi / t_1$; $t_1$is the time of the pressure surge leading edge; $p_0$is the pressure surge amplitude.

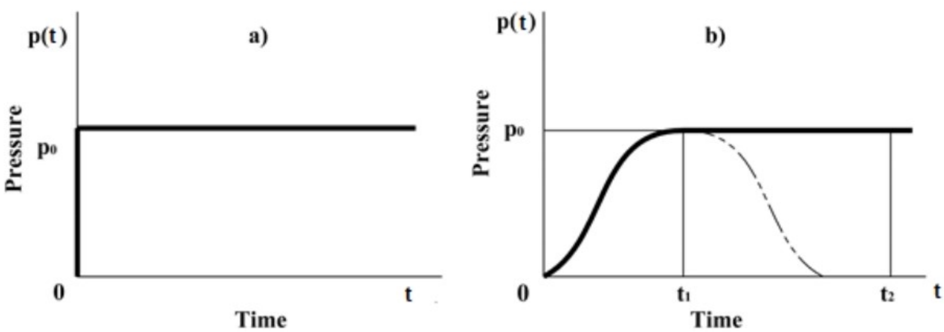

Fig. 1. Forms of test signals: a) ideal pressure surge; b) – real pressure surge.

It is known that the primary transducers in modern pressure sensors are elastic membranes, and therefore the dynamic model of the sensor represents the Volterra integral equation (convolution integral):

$$U(t) = k \cdot \int_0^t e^{-\beta(t-\tau)} p(\tau) \sin(\omega \cdot (t - \tau)) \, \mathrm{d}\tau, \tag{4}$$

where k is the static conversion ratio of the sensor; β is the damping ratio of the sensor membrane vibration; $p(\tau)$ is the pressure being measured; $\omega = \sqrt{\nu^2 - \beta^2}$ is the frequency of natural vibration of the membrane with damping; ν is the frequency of natural vibration of the membrane without damping.

To simulate tests, a real output signal is obtained by inserting (2) into (4). Thus, in the interval $\tau = 0, \ldots, t_1$:

$$U(t) = k \cdot \int_0^t e^{-\beta(t-\tau)} \frac{p_0}{2}(1 - \cos \eta\tau) \sin(\omega \cdot (t - \tau))\, \mathrm{d}\tau = k \cdot \frac{p_0}{2}[F_1 - F_2 - F_3], \tag{5}$$

where

$$F_1(t) = \frac{\omega - e^{\beta t}(\omega \cdot \cos \omega t + \beta \cdot \sin \omega t)}{\omega^2 + \beta^2},$$
$$F_2(t) = \frac{\beta}{2}\left[\frac{1}{\beta^2 + (\omega - \eta)^2}\left(\sin \omega t + \frac{\omega - \eta}{\beta} \cos \omega t\right) - e^{-\beta t}\left(\sin \omega t + \frac{\omega - \eta}{\beta} \cos \omega t\right)\right],$$
$$F_3(t) = \frac{\beta}{2}\left[\frac{1}{\beta^2 + (\omega + \eta)^2}\left(- \sin \omega t + \frac{\omega + \eta}{\beta} \cos \omega t\right) - e^{-\beta t}\left(\sin \omega t + \frac{\omega + \eta}{\beta} \cos \omega t\right)\right].$$

To obtain the output signal at $t \geq t_1$ we insert (3) into (4):

$$U(t) = e^{-\beta t}\left[\frac{\dot{U}(t_1) + \beta U(t_1)}{\omega} \sin \omega t + U(t_1) \cos \omega t\right] + k\left[p_0 \frac{\omega - e^{-\beta t}(\omega \cdot \cos \omega t + \beta \sin \omega t)}{\omega^2 + \beta^2}\right] \tag{6}$$

where $U(t_1)$ and $\dot{U}(t_1)$ is the output signal and the rate of its change at time t_1.

In the case of the ideal test impact, the output signal is obtained by inserting (1) into (4):

$$U_i(t) = kp_0\left[\frac{\omega - e^{-\beta t}(\omega \cos \omega t + \beta \sin \omega t)}{\omega^2 + \beta^2}.\right] \tag{7}$$

The difference between the ideal and real output signals in the time interval $t = 0, \ldots, t_1$ is:

$$\Delta_1(t) = U(t) - U_i(t) = -kp_0\left[\frac{\omega - e^{-\beta t}(\omega \cos \omega t + \beta \sin \omega t)}{\omega^2 + \beta^2}\right] + k\frac{p_0}{2}[F_1 - F_2 - F_3], \tag{8}$$

and in the time interval $t > t_1$:

$$\Delta_2(t) = U(t) - U_i(t) = e^{-\beta t}\left[\frac{\dot{U}(t_1) + \beta U(t_1)}{\omega} \sin \omega t + U(t_1) \cos \omega t\right]. \tag{9}$$

The values of $\beta\omega$ and ν are in the range from kHz to MHz for the real pressure sensors, therefore, the values $\Delta_2 \gg \Delta_1$. Thus, it is advisable to assess the adequacy of the real output signal using the (9).

Let us determine the time point at which the difference between the real and ideal output signals reaches its maximum value. To do this, we differentiate (9) regarding t and equate the obtained result to zero:

$$\frac{\partial \Delta_2(t)}{\partial t} = -e^{-\beta t}\left[\frac{\beta \dot{U}(t_1) + \beta^2 U(t_1) + \omega^2 U(t_1)}{\omega} \sin \omega t - \dot{U}(t_1) \cos \omega t\right] = 0,$$

then

$$t^* = \frac{1}{\omega} \operatorname{arc\,tg} \frac{\omega \dot{U}(t_1)}{\beta \dot{U}(t_1) + \beta^2 U(t_1) + \omega^2 U(t_1)}. \tag{10}$$

Since it is physically impossible to create an ideal test impact, we will always deal with a real effect. This will cause the real output signal to deviate from the accurate one and therefore lead to some test error, which is methodical error its essence. Therefore, the maximum difference (error) between the output signal obtained from the real test impact and the signal obtained from the ideal test impact will be considered a measure of the uncertainty of the test method or a methodical error of the method.

Let us represent the determined maximum difference between the real and ideal signals in the form of some relative methodical error of the test:

$$\delta_{\max} = \frac{\Delta_2(t^*)}{U_i(t^*)} \times 100\%, \tag{11}$$

where the values of the quantities included in this formula are determined at the time point obtained from (10).

Since it is physically impossible to create an ideal test impact, we will always deal with a real effect. This will cause the real output signal to deviate from the accurate one and, therefore, lead to some test error, which is a methodical error in its essence. Therefore, the maximum difference (error) between the output signal obtained from the real test impact and the signal obtained from the ideal test impact will be considered a measure of the uncertainty of the test method or a methodical error of the method.

The numerical analysis (11) with different ratios of values t_1 and ω shows the correlation between the methodical test error, dynamic parameters of the sensor, and parameters of the test impact (Fig. 2).

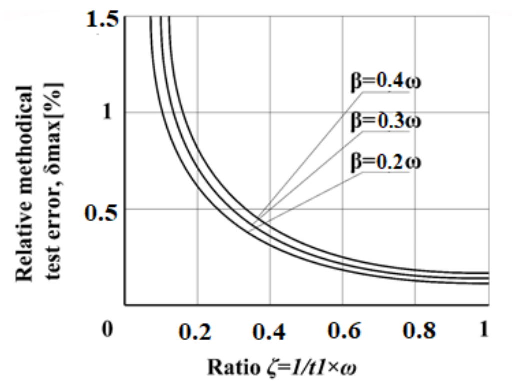

Fig. 2. Dependence of the maximum relative methodical test error $\delta_{\max}$ on the ratio $\zeta = \frac{1}{t_1\omega}$.

The obtained dependencies are interpolated by the function:

$$\delta_{\max}(\varsigma) \approx \frac{0.125}{\zeta}. \tag{12}$$

Then

$$t_1 \approx \frac{8 \cdot \delta_{max}}{\omega}. \tag{13}$$

For practical use, it is advisable to use the inequality:

$$t_1 < \frac{8 \cdot \delta_{max}}{\omega}. \tag{14}$$

Thus, having the value of the natural frequency of vibration of the sensor ω and setting the value of the permissible methodical error of the test $\delta_{\max}$, it is possible to determine the acceptable duration of the rise time of the test impact edge using the (14). This calculation allows reasonably selecting the device for testing the sensor and relying on the results obtained.

There may exist a physical process in which the rising of the pressure surge leading edge occurs according to another (not cosine) law. This, however, does not change the requirement for the duration of such leading edge rising. It must be below (14). Then, due to the effect of such pressure surge, we will obtain a transient characteristic of the sensor, which will differ from the one obtained for a square-wave surge by no more than $\delta_{\max}$, which is regarded as a methodical error.

4. The principle of creating a test impact and the device for dynamic calibration of pressure sensors

As noted earlier, when creating a pressure surge, it is difficult to achieve stability ($p(t) = p_0$ = const) on its steady part $t_1 \leq t \leq t_2$. As a rule, the reflected waves start to arise there, the vibration effects of the shock tube body appear, *etc.* i.e., $p(t) \approx$ const, which significantly complicates the test procedure since it reduces the reliability of the results obtained.

On the other hand, if the test impact represents not a rising, but a falling edge affecting a pre-deformed membrane, then the picture will be qualitatively similar to that described above. That is, if the fall time of the test impact corresponds to (14), then the real output signal will differ from the ideal one by no more than $\delta_{\max}$ percent.

That is why the dynamic calibration of pressure sensors is proposed to be carried out using a rapidly falling edge of the test impact on a pre-deformed membrane.

To carry out the dynamic calibration of sensors through a falling edge, a device has been developed, the general view of which is shown in Fig. 3, and the design diagram of the device is presented in Fig. 4.

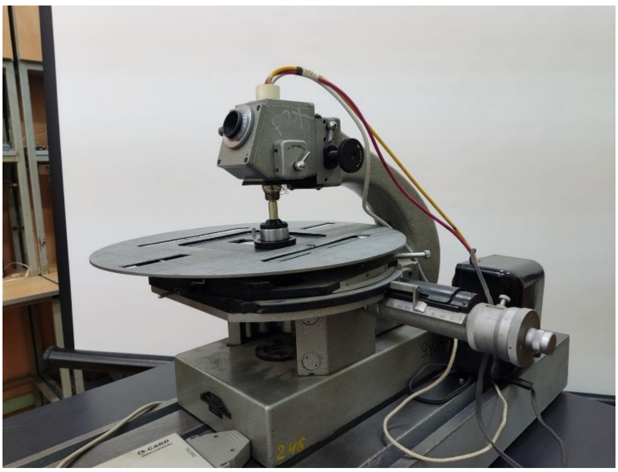

Fig. 3. Device for dynamic calibration of pressure sensors.

The device (Figs. 3 and 4) has a massive bracket with a base platform and a sensor holder. A unit for creating a test impact, consisting of a device for preliminary kinematic deformation of the sensor membrane with a micrometric feed and a piezoelectric rod, is fixed on the base platform.

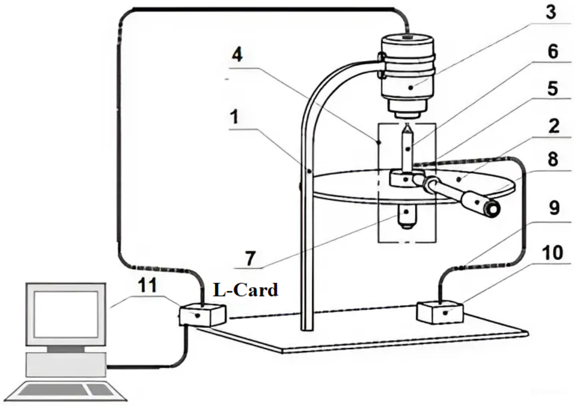

Fig. 4. Design scheme of the device for dynamic calibration of pressure sensors: 1 – bracket; 2 – base platform; 3 – sensor holder; 4 – unit for creating a test impact; 5 – device for preliminary kinematic deformation of the sensor membrane; 6 – piezoelectric rod; 7 – micrometric vertical feed; 8 – rod alignment device; 9 – power and control cable; 10 – control unit; 11- signal processing and visualization system.

The tested sensor is fixed in a holder above the unit for creating a test impact, and the piezoelectric rod is vertically directed towards the center of the sensor membrane.

At the top of the rod, there is a metal ball significantly smaller than the diameter of the membrane. The power and control cable from the control unit is connected to the rod. At that, the frequency of longitudinal piezo resonant vibration of the piezoelectric ceramic rod corresponds to the condition:

$$\varsigma > \frac{\nu}{16 \cdot \delta_{\max}}, \tag{15}$$

where ς is the frequency of longitudinal piezo resonant vibration of the piezoelectric ceramic rod, ν is the frequency of natural vibration of the sensor membrane.

5. Method for dynamic calibration of pressure sensors

A pressure sensor, the dynamic characteristics of which are to be obtained, is fixed in holder 3 (Fig. 4) with the membrane down towards the rod 6. The rod 6 is placed using micrometric feed 7 so that it creates a specified preliminary kinematic deformation of the sensor membrane. The appropriate voltage is applied to the piezoelectric rod 6 from the control unit 10 through the power and control cable 9. As a result of the reverse piezoelectric effect, the piezoelectric rod 6 shortens, and the membrane gets rid of kinematic deformation. Since the frequency of longitudinal resonant vibration of the piezoelectric rod 6 corresponds to the condition (16), the duration of the test impact edge will be

$$T < \frac{8 \cdot \delta_{\max}}{\nu}, \tag{16}$$

where T is the duration of the test impact edge.

As a result of the tests, the transient response of the sensor, the actual frequency of vibration of the sensor in the medium, and the decay time of the natural vibration are obtained.

DOI: 10.24425/mms.2024.150293

6. Dynamic calibration of a piezoresistive pressure sensor

A piezoresistive pressure sensor was taken for the research (Fig. 5).

Fig. 5. Pressure sensor.

The class of accuracy of the tested sensor is (0.2), its additional uncertainty in the temperature range 0. . . 60 ^{0}C (0.0028%/°C), and operating range 0. . . 0.25 MPa. It should also be noted that such sensors are made in the Research Laboratory of Smart Precision Microsystem and Robotic Tools, Lviv Polytechnic National University. The theoretical frequency of the natural vibration of the sensor is $\nu = 40.0$ kHz.

With such dynamic parameters of the sensor and the accepted permissible methodical error of tests $\delta_{\max} = 0.1\%$, the maximum duration of the signal edge must comply with the condition:

$$T < \frac{8 \times \delta_{\max}}{\nu} = \frac{8 \times 0.1}{40 \times 10^3} = 20.0 \text{ s}.$$

Since the frequency of longitudinal resonant vibration of the piezoelectric ceramic rod of the device was 250 kHz, the duration of the test signal edge will be 2 s, which fulfils the condition (14).

The consequence of the test effect during calibration is the corresponding output signal of the sensor, which is subjected to numerical processing in the signal processing and visualization system of the developed device.

The calibration result is shown in Fig. 6.

The received output signal of the sensor is its "inverse" transient response. By transforming the "inverted" transient characteristic relative to the horizontal axis, we obtain the usual transient characteristic (Fig. 7).

It can be established from the numerical processing of the sensor output signal that the real frequency of natural vibration of the sensor in air under normal conditions is 39.57 kHz, which corresponds to the theoretical natural frequency if the damping ratio of vibration is taken into account. In addition, from the transient characteristic, it can be established that the decay time of natural vibration for the tested sensor is 80 s in air under normal conditions. The analytical dependence for the transient response of the sensor can be established through numerical processing of the sensor output signal,. In this case:

$$h(t) = \frac{\nu - e^{-\beta \cdot t} \cdot [\nu \cdot \cos(\nu \cdot t) + \beta \cdot \sin(\nu \cdot t)]}{\nu^2 + \beta^2}, \tag{17}$$

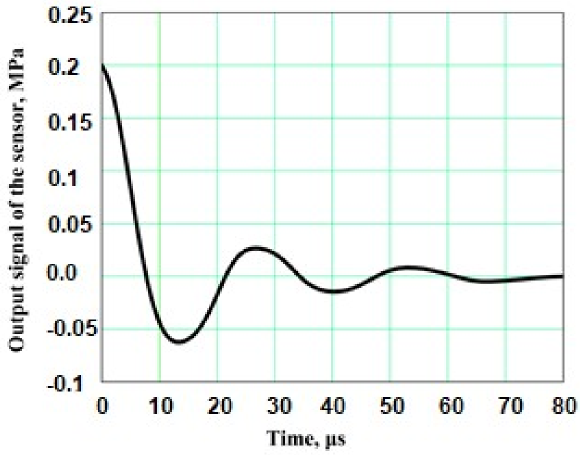

Fig. 6. Result of dynamic calibration of the pressure sensor.

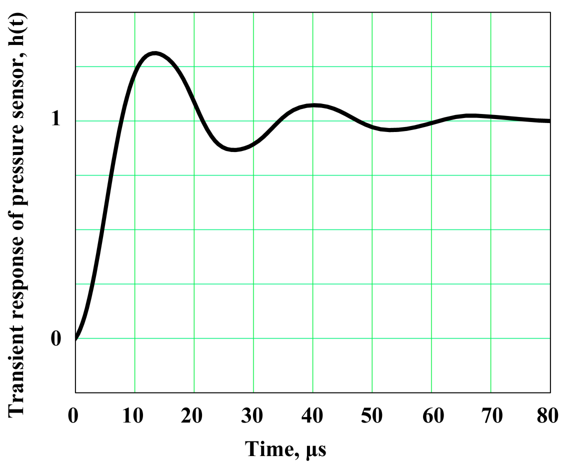

Fig. 7. Transient response of the pressure sensor.

where $\nu = 40.0$ kHz is the frequency of natural vibration of the sensor; β is the damping ratio of sensor membrane vibration, which depends on the measurement medium.

The damping ratio β is determined from the (17). For this, the ratio between the amplitudes of vibration at certain moments of time t_1 and t_2 is calculated, and then the obtained transcendent equation is solved numerically with respect to β.

All these parameters are obtained by digital processing of the output signal of the sensor using known applications (LabVIEW, Mathcad, MATLAB) or specialized software for processing measurement signals, which is a component of interface modules (e.g., L-Card, *etc.*).

Evaluation of uncertainty in sensor calibration. The required accuracy of the assessment of the dynamic parameters of the sensors is obviously determined by the scope of their application or the requirements of the measurement tasks for which the sensor is intended.

The main idea of the theoretical part of the work is to show that, depending on the permissible error of obtaining the transient characteristic (and this is the requirement of the measurement task), it is possible to set requirements for the test signal parameters and to understand what device can provide these conditions. First of all, this concerns the so-called methodical error in studying the dynamic characteristics of sensors. For example, the transient characteristic of the sensor is its output signal if a single square-wave surge (Heaviside step function) was fed at the input of the sensor. However, physically, a square-wave surge is impossible to create. Then, strictly speaking, we cannot obtain a transient characteristic. A real test impact has a certain duration of the edge, due to which we obtain an output signal that is close to the transient characteristic. This degree of proximity will be the error in determining the transient characteristic. This error, dynamic parameters of the sensor and duration of the edge are interrelated. The formula (16) in the article describes this relation. Therefore, the accuracy of obtaining the transient characteristic is determined by the duration of the edge of the pressure surge.

In the proposed device, the uncertainty of measurements is formed by the static error of the sensor, error of the duration of the test impact edge, and uncertainty of processing the output signal of the sensor.

Since the sensor is calibrated at strictly maintained normal conditions, its static error is constant. For known calibration methods (a shock tube or the method of dropping a load on a piston), a sharp increase in the pressure of the medium results in a change of its temperature, which influences the static error of the sensor. When calibrating in a shock tube, a pressure surge causes the vibration of the tube body, which affects the calibration accuracy. The same occurs in a cylinder with a piston. Besides, the complexity of the physics of the impact in its turn increases the uncertainty of measurements. Unfortunately, in the descriptions of the known calibration devices [8–15], the authors of the publications do not make clear a quantitative assessment of the influence of external destabilizing phenomena. There are no external phenomena in the developed device that can affect the calibration accuracy, due to which it will have better metrological parameters.

To create a test impact, the membrane must be subjected to a preliminary kinematic deformation to a value of one. This deformation is set with a micrometer screw. As the value of one level is set based on the output signal of the sensor, the error of the micrometric feed does not affect the calibration procedure and is contained in the static error of the sensor.

In the proposed device, the implementation of the principle of creating a test impact can cause only a methodical error. If the duration of release of the kinematically pre-deformed membrane fulfills the condition (16), the developed device has a methodical uncertainty below $\delta_{\max}$.

For processing the output signal of the sensor, an L-Card interface module was used. The use of a standardized interface module for processing an output signal enables *analog-to-digital conversion* (ADC) with a 14-bit rate and data collection at a frequency of up to 10 MHz.

As the application of digital processing of measurement signals is an option in almost all sensor calibration devices, then, based on the errors of signal processing, the existing calibration systems are comparable. Besides, for modern ADC there are software interfaces for correcting errors, which makes it possible to reduce them significantly. However, for every specific calibration device, the error of signal processing must be determined.

Based on the above, the main static error of the calibrated sensor was 0.2%. Since the duration of the test impact edge was 2 s, then based on the theoretical aspects presented in the paper, the error of obtaining the transient response will be 0.01%. To process the output signal of the sensor, we used an L-Card type interface module, the description of which indicates that its reduced error of signal conversion does not exceed 0.02%. The maximum uncertainty in calibration, therefore, will be 0.23%.

7. Discussion of the research results

The developed device for dynamic calibration of pressure sensors (Fig. 3) is significantly simpler in design and functionality than the known analogues [8–15]. The efficiency of the device is achieved due to the proposed principle of creating a test impact, the calibration method, and its design solution. The operation principle of the device is based on the correlation between the dynamic parameters of the sensor, the methodical error of tests, and the parameters of the test signal established in the study, which allows conducting tests with a known methodical error.

However, when conducting the research, it is necessary to ensure a strict alignment of the axis of the piezoelectric rod and the sensor membrane (the deviation from alignment should not exceed hundredths of the membrane radius), which is an additional complication. Therefore, in the developed device there is a mechanism for such a procedure (rod alignment device 8 in Fig. 4).

An obvious limitation in the use of the device will be the amplitude of the preliminary kinematic deformation of the membrane of the tested sensor, as there is a minimum pitch of the micrometric feed of the device.

The unit for creating a test impact in the developed device is designed for sensors with a certain range of amplitude of effect. The application for other types of sensors requires a different unit, which is a disadvantage of the device, as it is not universal. The disadvantage can be eliminated by developing several replaceable units for the test impact creation.

An important aspect of the further use of the device is the creation of appropriate metrological support and its certification. In addition, a significant improvement of the device will be to ensure its operation at different temperature modes and in the liquid medium.

The simplicity of design and mobility will allow the developed device to find its application both in testing laboratories for pressure sensors and in research institutions for modeling the dynamics of pressure sensors.

The developed device allows obtaining the transient response of the sensor (Fig. 7, (16)), as well as setting the decay time of its natural vibration. Based on the transient response, other dynamic characteristics of the sensor can be calculated, namely the impulse transient and frequency response. The decay time of the natural vibration of the sensor membrane makes it possible to indicate the permissible duty cycle of the impulse shock pressure, which often has to be measured in modern technical systems.

8. Conclusions

The paper presents a solution to the problem of correlation between the dynamic sensor parameters, methodical test error, and test signal parameters. The obtained analytical dependencies of this relationship allow reasonable selection or development of a method for studying the dynamic characteristics of sensors and a rational principle for creating a test impact.

Based on theoretical studies, the principle for creating a test impact in the form of a falling pressure edge is proposed. To implement this principle, the design of the unit was developed in the form of a device for preliminary kinematic deformation of the sensor membrane and a piezoelectric rod that instantly releases the membrane from deformation.

The method for dynamic calibration of pressure sensors has been developed, which consists in creating a preliminary kinematic deformation of the sensor membrane, with further impact of a falling edge by instantly releasing the membrane from deformation, recording and processing of the output signal.

The developed method of dynamic calibration of pressure sensors is implemented in the developed device for dynamic calibration of pressure sensors. The article presents the design of this device.

In the developed device, the uncertainty of measurements is formed by the static error of the sensor, error of the duration of the test impact edge, and uncertainty of processing the output signal of the sensor.

Experimental studies of the dynamic characteristics of the real pressure sensor on the developed device were carried out. The research resulted in obtaining the transient response of the sensor. The experimental studies of the dynamic characteristics of the real pressure sensor showed the effectiveness of the developed dynamic calibration device and confirmed the correctness of the scientific aspects of the research. The effectiveness of the device is primarily manifested in the ability to calibrate sensors with a known methodical error, as well as in the simplicity of the calibration procedure and its cost. Besides, there are no secondary physical phenomena during calibration (as in a shock tube or impulse power simulator) causing uncertainty in the calibration result.

It should be noted that in terms of performance, it is difficult to compare the performance of a shock tube, a pulse shock device and the device presented in the paper. In fact, the main criterion is the adequacy of the obtained dynamic characteristics. However, the developed device is cheaper than a shock tube or an impulse impact unit and is easier to maintain. Therefore, its operational characteristics are better.

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DOI: 10.24425/mms.2024.150293

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