Development and researches of vacuum gauges with sensitive elements created by MEMS technology

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Abstract. The article is devoted to the development and research of sensitive elements, transducers and vacuum gauges created by MEMS technology and intended for measuring absolute pressure in a wide range from \(10^{-3}\) to \(10^5\) Pa.

Currently in the sphere of low absolute pressure (vacuum) there is a number of problems, at first instance, connected with commercial unavailability of domestic high precision measuring facilities for measuring low absolute pressure. The following major problems can be outlined.

1. Lack of domestic comparison standard for carrying out collation between state primary standard GET 49-2016 and GET 101-2011, carrying out inter-laboratory comparisons, and also carrying out international collations.

2. Lack of domestic serially produced high precision measuring facilities conforming to the standard of 1 and 2 category by GOST 8.107-81. Since 2008 up to the present moment only two domestic produced vacuum gauges have passed trials for type approval, while their metrological characteristics do not meet requirements for the standards of 1 and 2 category [1].

3. Sanction restrictions, placed by Western countries, do not allow to procure a number of high precision measuring facilities of foreign production.

To solve mentioned problems D.I. Mendeleev Institute for Metrology proposed to develop domestic vacuum gauges, meeting the following specified requirements:

- Compact size of sensitive elements;
- Low dependency on the type of gas;
- Domestically produced components;
- Low cost.

Analysis showed that those requirements are most fully met by construction of sensitive elements produced by technology of microelectromechanical systems (MEMS). The results of research work, held proactively in the department of state standards in the sphere of pressure measurement [1], in 2017 allowed to start in D.I. Mendeleev Institute for Metrology experimental design work «Research and development of high precision deformation devices for measuring low absolute pressure in the range \(1\cdot10^{-3}\) - \(1\cdot10^4\) Pa, created by technology of microelectromechanical systems”.

It was decided to develop two types of prototype models: vacuum gauge, based on resonance method of pressure measurement and vacuum gauge, based on membrane-capacitance method using compensation and compression. At the stage of compiling technical design specification, requirements for metrological characteristics of the developed prototype models were formulated as follows (see Table 1).
Table 1 – Characteristics of prototype models

| Name of metrological characteristics | Value of metrological characteristics |
|--------------------------------------|----------------------------------------|
| Prototype model type 1               |                                        |
| Range of measurements                | from 10 Pa to $10^4$ Pa                |
| Relative measurement error           | not more than ±(2…1) %                 |
| Prototype model type 2               |                                        |
| Range of measurements                | from $10^{-3}$ Pa to 10 Pa             |
| Relative measurement error           | not more than ± (10 -2) %              |

Sensitive element of vacuum gauge (picture 1), with the principle of action based on measuring gas spring rigidity (resonance type), its construction represents a plate on the hangers, placed between fixed planes.

![Picture 1 – draft of sensitive element of resonance type](image1)

Gas spring is formed by electrodes plane №1 and №2, and also by siliceous movable plate as shown on picture 2.

![Picture 2 – Construction of sensitive element of resonance type](image2)

Metrologically significant dimensions of sensitive element of the resonant type are shown at picture 3.
Metrologically significant dimensions of sensitive element

where:
- $h$ - thickness of movable plate;
- $Z_1$ - reference value of gap (gas spring) №1;
- $Z_2$ - reference value of gap №2.

Resonant frequency of plate vibration depends on the gas spring rigidity.

$$f_p^2 = \frac{G_m + G_p}{4 \omega^2 m},$$

where $G_m$ - mechanical rigidity of a plate, $G_p$ - pneumatic rigidity of a gas spring, $m$ – weight of a movable plate.

Electrical scheme of pressure transducer of the resonance type is shown on picture 4.

In general case parameters of plate movement are described by the following equation:

$$m \frac{d^2 y}{dt^2} + B \frac{dy}{dt} + G \cdot y - \frac{\varepsilon \varepsilon_0}{2(Z+y)^2} (U_1^2 - U_2^2) \cdot S = 0,$$

where $y=a \cdot \sin(\omega \cdot t)$ - functional relation of plate movement, $a$ - amplitude of vibration, $\omega$ - circular frequency of vibration, $B$ - coefficient of viscous friction power of gas environment, $G$ - rigidity, $\varepsilon$ – dielectric permeability of gas environment, $\varepsilon_0$ – dielectric constant, $U_1$ u $U_2$ – electrical voltage on electrodes.

The dependence of resonance frequency of plate movements on the gas pressure can also be obtained by the method of small displacements, if equate amount of energy, stored in gas spring, to
changes in vibrating system energy. In this case the dependency of measured gas pressure on the
frequency of plate vibrations can be presented as follows:

\[ P = 2 \cdot \rho \cdot h \cdot Z \cdot f^2, \tag{3} \]

where \( \rho \) – density of plate material.

Dependence of the pressure on squared frequency of movements is linear:

\[ P = K \cdot f^2, \tag{4} \]

where \( K = 2 \cdot \rho \cdot h \cdot Z \) – coefficient of conversion, can be calculated from material density
and value of geometrical dimensions of a movable plate.

Picture 5 shows an experimental dependence of pressure on squared frequency, received in the
process of prototype model trial.

The functional relation of approximation showing that tangent of inclination angle of the straight
line equals 3.18e-4 \( \frac{P_a}{gh^2} \), is also displayed on the diagram. This value coincides with earlier calculated
value of the coefficient of conversion \( K \).
The second type of a sensitive element, created by MEMS technology, is based on gas pressure measuring by electrostatic pressure compensation and in its construction represents a membrane with plane-parallel distributed electrodes (picture 8).

Membrane deformation, created when supplying measured gas pressure, is compensated by electrostatic negative pressure (while providing constant voltage to the measuring electrode). The formula of conversion is as follows:

$$ P = \frac{\varepsilon_0}{2h^2} \cdot U^2, $$

where $\varepsilon_0$ - dielectric constant, $h$ - value of gap between membrane and measuring electrode plane, $U$ - value of constant voltage, at which compensation of membrane deformation took place.

The third type of sensitive element, created by MEMS technology, in its construction is similar to the sensitive element of the resonance type, with the difference that not gas spring rigidity is measured, but the value of power loss (work against force of friction on the gas side) with vibratory movement of a plate. The principle of action of the sensitive element of this type is illustrated on picture 9.
Principle of measuring the value of power loss with vibratory movements of a sensitive element plate

Composite plate with weight \( m \) on mechanical hangings with rigidity \( k \) makes forced vibrations \( z(t) \), approaching by its form to harmonic. In the process of movement the plate plane experiences power on the side of gas, that is proportional to absolute gas pressure. To maintain certain amplitude of forced vibrations it is required to replenish energy spent for work against power on the side of gas. The energy is replenished by electrostatic actuator \( y(t) \). The amount of replenished energy is proportional to absolute gas pressure.

The results of vacuum gauge calibration, using sensitive element, embodying the principle of measuring energy loss, are shown on picture 10.

![Picture 9](image)

Picture 9 – Principle of measuring the value of power loss with vibratory movements of a sensitive element plate

On the \( x \)- axis the pressure in Pascal is displayed, on the \( y \)- axis – energy loss in conventional units (\( \% \)) is displayed. It should be mentioned that with the increase of pressure energy loss increases non-linear.

Picture 10 shows a diagram which allows to estimate sensitivity of the method (the first derivate of calibration curve) depending on the absolute gas pressure.
Sensitivity of the method in dependence on absolute gas pressure

It is evident from the diagram that sensitivity decreases by 2 points under the pressure over 10000 Pa. The results of vacuum gauge calibration, actualizing method of measuring energy loss, were held with the use of standard vacuum gauge MKS Baratron and are represented in table 2.

Table 2 – Results of vacuum gauge calibration

| Value of MEMS-vacuum gauge, Pa | Value of standard, Pa | Relative error, % | SKO, % |
|-----------------------------|----------------------|------------------|-------|
| 60.68                       | 60.64                | 0.1              | 0.6   |
| 91.7                        | 91.81                | -0.1             | 0.4   |
| 111.6                       | 111                  | 0.6              | 0.3   |
| 301.5                       | 301.7                | -0.1             | 0.1   |
| 600.3                       | 599.5                | 0.3              | 0.4   |
| 897.4                       | 893                  | 0.4              | 0.3   |

The external appearance of vacuum gauge with transducers, created by MEMS technology, is shown on picture 12.

![Picture 12 – Vacuum gauge of the resonance type](image)

The results of the research allow to deduce an inference, that developed models satisfy the requirements of technical design specification, and allows to continue work on creation of serially
produced wide-frequency-band precision vacuum gauge, using several sensitive elements at once, created by technology MEMS and actualizing various principles of measuring absolute pressure.

References
[1] V.N. Gorobey, A.Y. Garshin, R.E. Kuvandykov. “Resonant subatmospheric transducer, created on technology MEMS” Vacuum technique and technology -2017. Contributions to 24-й All-Russian scientific-technical conference with international participation 06.06.2017.