Some features of the development of a deformation frequency-response vacuum gauge for measuring low absolute pressures

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Abstract. The article shows the tasks involved in developing a deformation frequency-response vacuum gauge for measuring low absolute pressures. The calculations of the parameters of the measuring transducer are given, which made it possible to create a competitive and inexpensive device.

The motivation for developing a vacuum gauge for the range of low absolute pressures in the range of 10-1000 Pa is due to the fact that pressure measurements in this range are fundamental for a wide range of vacuum technologies. We have already emphasized that these measurements are of great importance for a number of industries that are associated with the use of vacuum in technological processes and increased demands on the quality of the manufactured products [1]. Vacuum measurements are especially important in the nuclear, aerospace, electronics, metallurgy, and other high-tech industries. In this context, the range of equipment for measuring low absolute gas pressures (vacuum) is being expanded. In recent years, for example, a number of different types of precision instruments for measuring low absolute pressures of a new generation have appeared on the Russian Federation market, which unfortunately come mainly of foreign manufacturers [2, 3]. First of all, these are different types of high-precision vacuum gauges. These include deformation, viscose, thermal and some other types of vacuum gauges, as well as various vacuum gauges whose metrological provison requires the improvement of the reference base. There is no doubt that its modernization is an urgent task today. For their solution based on D.I.Mendeleyev Institute for Metrology VNIIM a series of work is in progress to develop domestically competitive vacuum gauges which, among other things, meet requirements such as compact dimensions of the measuring transducer; were made from components of the domestic composite production; would have a low market value.

Let's calculate parameters of the measuring transducer. The transducer developed for a deformation frequency-response vacuum gauge [4] is a mechanical oscillating system and consists of three flat parallel plates (two rigidly attached and one movable between them), which are arranged with a gap. The movable plate (hereinafter MP) is attached to the fixed frame with the help of suspension beams. The MP can move perpendicular to its plane (one degree of freedom). The transducer construction is shown in cross section in Figure 1.

In the cross section of the transducer, the conductive MP is marked with the number 1, frame 2, suspension of MP with a coefficient of stiffness equal to $G_m$, 3, electrodes 4, gas inlet channel 5, measurement gas gaps 6, plates of dielectric material 7.
Harmonic oscillations of the MP with the mass m and the displacement of the MP from the central position \( x(t) = a \sin(\omega t) \), with no gas in the measurement gas gaps (\( P \approx 0 \) - the gas pressure \( P \) on 2-3 orders smaller than the lower measurement limit of the vacuum gauge) the movement of the MP is described by equation (1) of a harmonic oscillator with one degree of freedom [5].

\[
\ddot{x} + \omega^2 x = 0,
\]

where \( \omega \) – is the resonant circular frequency of the MP equal to the square root of the ratio of the coefficient of elasticity of the mechanical suspension to the MP mass \( \omega = \omega_m = \sqrt{\frac{\sigma_m}{m}} \).

If gas is present in the measuring gas gaps (\( P > 0 \)) with harmonic oscillations of the MP, the volumes of the measuring gas gaps changing and, according to the Boyle-Mariotte law, the gas pressure in them changes, i.e. the coefficient of stiffness of the measuring gas gaps appears (the ratio the force acting on MP from the gas side leads to a change in the size of the gap).

Figure 2 shows the dimensions of the measuring transducer.

Figure 2 shows: \( h \) - MP thickness; \( Z \) is the initial value of the gas gap values.
As shown in [6], the coefficient of stiffness of gas gaps $G_g$ at gas pressure $P$ and area of MP $S$ is determined by formula (2).

$$G_g = \frac{2PS}{Z}$$ (2)

Thus, when gas is present in the gaps between the MP and the electrodes, the resonant circular frequency is determined by the formula (3).

$$\omega = \sqrt{\frac{G_M + G_g}{m}}$$ (3)

Considering that $\omega=2\pi f$, where $f$ is resonant frequency of MP oscillations, $\omega=2\pi f_m$, we get the measurement equation (4).

$$P = K(f^2 - f_m^2)$$ (4)

where $K=2\pi^2\rho h Z$ – is conversion coefficient ($\rho$ – density value of MP material).

The principle of operation of such a measuring transducer is to convert the value of the measured absolute gas pressure into the value of MP oscillations frequency.

If the MP deviates from the middle position by the value $x$, the force $F_g$ acts on the MP from the gas side, determined according to formula (5).

$$F_g = PS\left(\frac{Z}{1+x} - \frac{Z}{1-x}\right)$$ (5)

Assuming as a first approximation that the displacement of the MP from the middle position relative to the thickness of the gas gap is insignificant and is $x = 0.01Z$, then the formula (5) takes the form (6).

$$F_g = PS\left(\frac{1}{1-0.01} - \frac{1}{1+0.01}\right) \approx 0.02PS$$ (6)

As can be seen from the formula obtained, the force $F_g$ is proportional to the pressure. At high pressures, the force $F_g$ can increase so much that the electrostatic actuator cannot move and hold the circuit board. To this force $F_g$ it is necessary to add a mechanical force from the side of the suspension of the plate, but at high pressures it is several orders of magnitude less than $F_g$, so we will not take this into account in the calculations. To calculate the electrostatic force, you need to know the value of the electrical voltage between the MP and the electrode, as well as the dependence of the change in capacitance on the displacement. The capacitance of a flat capacitor, the plates of which are formed from the MP and a flat electrode without taking edge effects into account, is determined by formula (7).

$$C(Z) = \frac{\varepsilon \varepsilon_0 S}{Z},$$ (7)

where $\varepsilon$ is the relative dielectric permittivity equal to 1 for vacuum and air; $\varepsilon_0$ is an dielectric constant of 8.85 pF/m.

The energy of the electrostatic field of such capacitor is determined by the formula (8).

$$E = \frac{CU^2}{2} = \frac{\varepsilon \varepsilon_0 SU^2}{2Z},$$ (8)

where $U$ is the constant electrical voltage between the MP and the electrode.

The electric force is defined by the formula (9) as the energy difference [7].
The modulus of electric force is determined by the formula (10).

\[ F_e = \frac{dE}{dZ} \]  

(9)

The electric force must be greater than the force acting on the MP from the gas side, as indicated in inequality (11).

\[ F_e > F_g \]  

(11)

Taking into account the formulas (6) and (10), we can write the inequality (12).

\[ \frac{U^2 \varepsilon \varepsilon_0 S}{2Z^2} > 0.02PS \]  

(12)

If we reduce the factor S on the left and right side of the inequality with \( P = 1000 \) Pa (upper measuring range) and limit the DC voltage between the printed circuit board and the electrode \( U = 10 \) V, we get the thickness of the gas gap: \( Z < 5 \) µm. In consultation with the manufacturer, the value of the gas gap thickness \( Z = 3 \) µm was chosen. When the MP oscillates, some quantity of the gas can flow out of the gas gap between the MP and the electrodes or flow in through the side surfaces of the gas gap (figure 3).

![Figure 3. Location of the side surfaces of the gas gap.](image)

The flow of gas with MP oscillations violates the possibility of applying the Boyle-Mariotte law when calculating the conversion coefficient \( K \) according to formula (4). Let us consider the gas leakage through the side surfaces of the gas gaps during the MP oscillations. The gas gap is limited by the dimensions of the MP \( a \) and the thickness \( Z \).

The area \( S_s \) of the lateral faces of a parallelepiped that describe a gas gap can be calculated using formula (13).

\[ S_s = 4aZ \]  

(13)

The total surface area \( S_p \) of the parallelepiped that describe a gas gap is determined by formula (14).

\[ S_p = 2a^2 + S_s \]  

(14)

The ratio of the area of the side surfaces to the total area of the gas gap can be expressed by formula (15).
In order to ensure a low gas leakage through the side surfaces of the gas gap, we can write the condition or thus the inequalities (16), (17), (18) and (19).

\[
\frac{S_s}{p} = \frac{S_s}{2a^2 + S_s} \tag{15}
\]

In order to ensure a low gas leakage through the side surfaces of the gas gap, we can write the condition or thus the inequalities (16), (17), (18) and (19).

\[
S_s < 0.01(2a^2 + S_s) \quad \tag{16}
\]

\[
0.99S_s < 0.02a^2 \quad \tag{17}
\]

\[
0.99 \cdot 4aZ < 0.02a^2 \quad \tag{18}
\]

\[
a > 200Z \quad \tag{19}
\]

In order to reduce the influence of gas leaks through the lateral faces of the gas gap on the sensitivity of the frequency-response vacuum gauge, the following condition must be met: \(a > 200Z\). Taking \(Z = 3\ \mu m\) into account, we find: \(a > 0.6\ \text{mm}\).

Taking into account the formulas (2) and (3) and assuming that \(G_m < G_g\) applies as a first approximation, 2 is determined according to formula (20).

\[
\omega^2 = \frac{G_r}{m} = \frac{2PS}{Zm} = \frac{2PS}{ZphS} = \frac{2P}{Zph} \quad \tag{20}
\]

Considering that \(\omega = 2\pi f = \frac{2\pi}{T}\), where \(T\) is the period of the MP oscillation, we can write down equations (21) and (22).

\[
\frac{4\pi^2}{T^2} = \frac{2P}{Zph} \quad \tag{21}
\]

\[
T^2 = \frac{4\pi^2 Zph}{2P} = \frac{2\pi^2 Zph}{P} \quad \tag{22}
\]

In order to meet the condition of a small gas leak through the lateral faces of the measurement gas gap in the case of MP oscillations, the period of oscillation must be less than 1 millisecond: \(T < 10^{-3}\), then \(T^2 < 10^{-6}\). Then we can write inequalities (23) and (24).

\[
\frac{2\pi^2 Zph}{P} < 10^{-6} \quad \tag{23}
\]

\[
h < \frac{10^{-6} P}{2\pi^2 Z\rho} \quad \tag{24}
\]

If you take into account that the lower measuring range of the vacuum gauge is \(P = 10\ \text{Pa}\), we get \(h < 90\ \mu m\).

Based on the results of the above-mentioned study and in consultation with the manufacturer, the parameters given in Table 1 were approved for the manufacture of the measuring transducer.

| Name of the characteristic | Value |
|----------------------------|-------|
| The size of MP \(a\), m    | 0.9\cdot10^{-3} |
| The thickness of the gas gap \(Z\), microns | 3 |
| MP thickness \(h\), m       | 75\cdot10^{-6} |
Figure 4 shows a photo of the external view of the transducer for the frequency-response vacuum gauge, manufactured with the technology of microelectromechanical systems [8].

In the course of developing a frequency-response vacuum gauge for measuring low absolute pressures, we have succeeded in creating an absolutely competitive and cost-effective device suitable for certification and series production for use under laboratory conditions and in industry. This was made possible by the compact size of the measuring transducer and the use of components from domestic production.

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