Development of design solutions for improving the characteristics of capacitive sensitive elements of sensors of physical quantities

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Abstract. Capacitive measuring transducers are the most stable of the sensors of physical quantities, so they are used in such areas and on products in which the parameters of time and parametric stability are the main parameters. Such products and systems include rocket and space technology, aviation, military equipment and weapons. In addition, capacitive measuring transducers are energy-saving, since the sensor element does not consume electrical energy during operation. To achieve high time and parametric stability, the design of measuring transducers must be designed using certain design and technological solutions aimed at eliminating the occurrence of unintentional internal mechanical stresses, and compensating for thermal stresses. In addition, capacitive measuring transducers must be guaranteed to be sealed, and also during their manufacture, all parts undergo a degassing operation, in which moisture dissolved in the near-surface layers of materials is removed by heat treatment in vacuum, as well as using methods of heterization of vacuum cavities.

1. Introduction
The fundamental conditions for creating technically advanced capacitive sensors (CS) are:

\[ \frac{W}{\epsilon_1 + \epsilon_2} \rightarrow 1 \quad \text{and} \quad \frac{W}{h_0} \rightarrow 1 \]

where is the deflection of the membrane, \( l_1, l_2 \) and \( h_0 \) are the geometric parameters of the membranes.

From the analysis of the above conditions, it follows that it is necessary to strive to increase both the absolute and relative deflection of the membrane elastic element of the pressure sensor.

The deviation of the rigid center of the membrane is equal to [1]

\[ W = A_p \frac{PR^2}{64D}, \]

where \( D = \frac{E\epsilon_1}{12(1-\mu^2)} \) is the stiffness of the membrane; \( A_p = (1 - \gamma^2 + 4\gamma^2 \ln \gamma) \) - normalization factor, \( r \) - the radius of the rigid center of the membrane.
The deflection \( W \) must satisfy the condition \( \sigma_{\text{max}} \leq \sigma \), where \( \sigma_{\text{max}} \) - maximum stress in the membrane at the surface points on the outer and inner contours of the elastic part; \( \sigma \) - the permissible stress for the membrane material.

\[
\sigma_{\text{max}} = B_p \frac{E t W}{R^2},
\]

where \( B_p = \frac{4}{1 - \mu^2} \left( \frac{1 - h^2}{1 - \gamma^4 + 4\gamma^2 \ln \gamma} \right) \).

The maximum possible deviation of the membrane is [2]:

\[
W_{\text{max}} = A_p \frac{R}[\sigma]^{1/2} (1 - \mu^2)
\]

where \( A_p = \frac{1 - \gamma^4 + 4\gamma^2 \ln \gamma}{2\sqrt{3}(1 - \gamma)^{1/2}} \).

From the analysis of this relationship, it follows that an increase in the absolute value of the deflection can be achieved by increasing the size of the membrane and choosing a membrane material that corresponds to the complex indicator

\[
A_p = \frac{1 - \gamma^4 + 4\gamma^2 \ln \gamma}{2\sqrt{3}(1 - \gamma)^{1/2}},
\]

which combines the mechanical characteristics of the selected material.

2. Materials and methods

By selecting a material with a maximum value of \( \psi \), you can increase the deflection by 3-4 times. However, this conclusion is valid only if the membrane material is not subject to important requirements, such as: high corrosion resistance, vacuum density, weldability of various types of welds, polishability up to 13-14 kl. Purity, low temperature coefficient of linear expansion (TCLE) and, most importantly, low temperature coefficient of elastic modulus \( \beta \) (TKEM) in a wide temperature range, since it is the value of this coefficient that determines the temperature multiplicative error of the developed capacitive quasi-differential pressure sensors [3, 4].

Taking into account the latter condition, a complex indicator that determines not only the deflection of the membrane, but also its heat resistance, can be presented in the form:

\[
\psi' = \frac{[\sigma]^{1/2} (1 - \mu^2)}{E \beta}.
\]

Then, of course, when choosing a structural material for elastic elements of capacitive pressure sensors, preference should be given to elinvar alloys, such as типа 29N26KHTBYU, EP-920, VUS-22, which have the maximum values of the indicator \( \psi' \): 4·10^6, 2.5·10^6, 22·10^6 [5]. In this case, it is possible to reduce the temperature error of pressure sensors by an order of magnitude in comparison with sensors made of 36 NHTYU alloy (\( \psi' = 0.5·10^6 \)). An increase in membrane deflection can be achieved due to the planned radial profiling of the membrane thickness (figure 1) according to the expression [6]

\[
\frac{t_{r'}}{t_r} = e^{\frac{\psi' \gamma^2}{\sigma}},
\]

where \( \varphi \) is a constant value; \( \sigma \) is the elastic limit.

The deflection in the center of such a membrane (figure 1a) can be represented by the formula:
where \( \eta = f(\varphi) \) - the value of this function at \( \mu = 0.3 \) for negative values of \( \varphi \) is given in table 1.

The graph of the dependence of this ratio on the coefficient \( \psi \) is shown in figure 1b: \( f(\varphi) = \frac{W_0'}{W_0''} \)

![Figure 1. Membrane of variable thickness (a) and its load characteristic (b).](image)

| \( \varphi \)  | 0   | -1  | -2  | -3  | -4  | -5  |
|---------------|-----|-----|-----|-----|-----|-----|
| \( \eta \)    | 0.0313 | 0.0246 | 0.0192 | 0.0152 | 0.0152 | 0.0119 |

Let us compare the deflections of a profiled membrane calculated from (7) and a flat membrane with a thickness \( t_i \) (thickness in the seal).

Deflection of the flat membrane:

\[
W_0' = \frac{\mu (1 - \mu^2) R^2 P}{E t_i'}.
\]

It follows from the graph that by profiling the membrane in thickness, it is possible to increase the deflection by almost 3 times.

Similar studies of a membrane with a rigid center have shown that the profiling effect is reduced several times, but remains significant (30%) at the ratio \( r/R = 0.2 \).

In the practice of creating sensors, there are requirements for maintaining metrological characteristics (MC) after exposure to overload pressures from 150 to 300% of the nominal ones. This requirement in sensors is most often achieved by calculating the membrane with a 50% margin for deviation and initial clearance.

The rejection of reserves for deflection and initial clearance (while ensuring the sensor's operability in the event of overload in another way) reduces the measurement error by about 1.5 times.

Summing up the results of the conducted research, it can be concluded that by selecting a structural material with the maximum value of the complex index \( \psi' \), as well as by profiling the thickness of the elastic element of the capacitive pressure sensor and reducing the deflection margin, it is potentially possible to reduce the measurement error many times (by 30-40 times) [7-9].

3. **Analytical estimation of the temperature error of a quasi-differential thin-film capacitive pressure sensor**

The process of converting pressure \( P \) to the ratio of capacities is carried \( C_0/C_x \) out in two stages:

1. Conversion of pressure to deflection (displacement) of the membrane (working electrode) \( P(W) \).
2. Conversion of displacement to the ratio of capacities \( W \) \( (C_0/C_x) \).
A change in temperature, as noted earlier, can lead to the following changes in the capacitive sensing element (CSE) parameters [10]:

- pressure in the zamembrane cavity,
- geometric dimensions of the membrane,
- elastic modulus of the membrane material,
- the dielectric constant of the medium between the electrodes,
- the area of the electrodes,
- the gap between the electrodes.

Changes in these parameters, in turn, cause the corresponding temperature conversion errors.

We will analyze the temperature errors for the above two stages of transformation using the example of an CSE with a membrane having a rigid center.

4. Analysis of the error caused by the change in pressure in the zamembrane cavity

In our opinion, it is advisable to analyze three possible physical states in practice of the transmembrane cavity CSE:

1. The zamembrane cavity is not sealed and interacts with the external environment, which can be very different in its properties, chemically neutral or aggressive.
2. The membrane cavity is sealed from the external environment, but contains dry air under pressure \( P_0 \). Since the possible temperature change lies in the range from minus 253 to + 640 °C, almost all the main gas components located in the zamembrane cavity at a temperature of minus 253 °C will pass from the gas to the liquid and solid phases. In this case, there will be a sharp increase in their dielectric constant (up to about 1.4).

Based on physical considerations, it is not difficult to see that the most likely place of gas condensation during the pressure conversion of cryogenic components is the electrode located on the membrane. It is for this reason that successive sharp changes in the output signal can be observed. Hence, it is natural to conclude that both of the considered states of the CSE zamembrane cavity are practically unacceptable for solving the problem. In order to avoid the occurrence of the considered temperature error, it is necessary to perform deep vacuum evacuation of the CSE membrane cavity to the value of the residual pressure significantly lower than the converted one.

In practice, this requirement for a number of technical reasons may not be completely feasible, then the value of the residual pressure should be determined based on the permissible value of the temperature error.

The relationship between pressure, temperature, and volume is described by the Mendeleev-Klayperon equation, one of the most simplified forms of writing, which has the form:

\[
P V = \frac{P_0 V_0}{T_0} = \frac{T}{T_0}
\]

(9)

where is \( P_0 \) the pressure at temperature \( T_0=273.1 \) K; \( V_0 \) -is the volume occupied by a gram-mole of gas at \( T_0 \); \( T \) - absolute temperature; \( P \) - gas pressure; \( V \) - gas volume.

If we neglect the change in volume \( V \) and pressure \( P \) in the zamembrane cavity due to the movement of the membrane, then according to when the temperature changes by an amount \( \Delta T = T - T_0 \), a corresponding change in pressure

\[
\Delta P = P_0 \frac{\Delta T}{T_0}
\]

then it will be determined by the relation

\[
P = P_0 + P_0 \frac{\Delta T}{T_0} = P_0 \left( 1 + \frac{\Delta T}{T_0} \right)
\]

Dividing both parts of the expression by the value \( P_0 \) (nominal pressure), we get

\[
\frac{\Delta P}{P_0} = \frac{P}{P_0} \frac{\Delta T}{T_0}
\]

(10)

Given that \( \Delta P/P_0 \) there is nothing but a relative reduced error, we find
\[
\gamma_p = \frac{P_0 \cdot \Delta T}{P_s \cdot T_0}
\]  

(11)

The error \(\gamma_p\) caused by the change in pressure in the zamembrane cavity is additive, and its relative influence increases with a decrease in the pressure range. Based on this analysis, we conclude that at low pressures, the zamembrane cavity must be evacuated.

5. Analysis of the error caused by changes in the elastic modulus of the membrane material and its geometric dimensions

The error under consideration occurs at the stage of converting the pressure into the movement of the electrode. \(P_s(W)\). The expression for the displacement of a membrane with a rigid center can also be represented as \([11]\):

\[
W_0 = A_p \cdot \frac{R_0^4}{E_0 t_0^3} P_s,
\]

(12)

where \(A_p = \frac{3(\mu^2 - 1)}{16} \gamma_0 \left(\frac{1}{1 - 4\gamma_0} - 1\right) \ln \gamma_0\); \(\gamma_0 = \frac{r_0}{R_0}\); \(R_0\) - the outer radius of the membrane; \(r_0\) - the radius of the rigid center; \(t_0\) - the thickness of the membrane outside the rigid center.

Let us \(A_p \cdot \frac{R_0^4}{E_0 t_0^3} = A_p'\) denote, then the expression (12) can be represented as

\[
W_0 = A_p' \cdot P_s
\]

(13)

When the temperature changes by \(\Delta T\), the parameters \(E, R, r, t_i\) in the framework of the linear theory of thermal conductivity will be determined by the expressions \(E = E_0(1 + \beta \Delta T)\), \(R = R_0(1 + \alpha \Delta T)\), \(r = r_0(1 + \alpha \Delta T)\), \(t_i = t_i(1 + \alpha \Delta T)\), where \(\alpha\) is the TCLE of the membrane material; \(\beta\) is TKEM of the membrane material.

The expression for the deflection of the membrane, taking into account the pressure in the zamembrane cavity, but without taking into account the temperature change, will have the form

\[
W_{0p_0} = A_p' \left( P_s - P_0 \right)
\]

(14)

Based on (12), taking into account (13) changes in temperature and pressure in the membrane cavity, the expression for the membrane deflection can be written

\[
W = A_p' \frac{1 + \alpha \Delta T}{1 + \beta \Delta T} \left[ P_s - P_0 \left( 1 + \frac{\Delta T}{T_0} \right) \right]
\]

(15)

or

\[
W = \frac{1 + \alpha \Delta T}{1 + \beta \Delta T} \left( W_0 - W_{00} - \Delta W_{W_0} \right)
\]

(16)

where \(W_{00} = A_p' \cdot P_0\) is the deflection of the membrane under the influence of the residual pressure of the zamembrane cavity;

\[
\Delta W_{W_0} = A_p' \cdot P_0 \frac{\Delta T}{T_0} - \text{change the deviation } W_{0p_0} \text{ from the temperature change to } \Delta T.
\]

The relative change in the deflection taking into account the change in temperature and pressure in the zamembrane cavity will be equal

\[
\frac{\Delta W}{W_{0p_0}} = \frac{W - W_{0p_0}'}{W_{0p_0'} - W_{0p_0}} = \frac{A_p' \frac{1 + \alpha \Delta T}{1 + \beta \Delta T} \left[ P_s - P_0 \left( 1 + \frac{\Delta T}{T_0} \right) \right] - A_p'(P_s - P_0)}{A_p'(P_s - P_0)} = \frac{1 + \alpha \Delta T}{1 + \beta \Delta T} \left[ P_s - P_0 \left( 1 + \frac{\Delta T}{T_0} \right) \right] \frac{P_s - P_0}{P_0}
\]

(17)
6. Results and conclusion

Analyzing the expression (17), it is easy to see that when the temperature changes, some compensation for the change in the deflection of the membrane occurs, due to changes in the parameters $\alpha$ and $\beta$ due to changes in the pressure in the cavity behind the membrane. When choosing a structural material for the membrane, the determining factor is the parameter $\beta$. It is important not only to select a low $\beta$ construction material, but also to normalize it over the entire operating temperature range [12].

![Figure 2](image-url)

**Figure 2.** Topology (a) and photography (b) of differential CSE: 1 и 3; 6 и 8; 5 и 7; 2 и 4 – topological axes CSE; R1-R5 - film electrode radii; $C_x$, $C_0$, $C_c$ - capacitive elements, $r$ – радиус of the CSE.

To ensure the parametric and temporal stability of capacitive sensors, mathematical models and design solutions for CSE are proposed, which ensure the physical and design compatibility of materials and assemblies (figure 2).

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