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NEW TYPE OF PIEZORESISTIVE PRESSURE SENSORS FOR ENVIRONMENTS WITH RAPIDLY CHANGING TEMPERATURE

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Abstract

The theoretical aspects of a new type of piezo-resistive pressure sensors for environments with rapidly changing temperatures are presented. The idea is that the sensor has two identical diaphragms which have different coefficients of linear thermal expansion. Therefore, when measuring pressure in environments with variable temperature, the diaphragms will have different deflection. This difference can be used to make appropriate correction of the sensor output signal and, thus, to increase accuracy of measurement. Since physical principles of sensors operation enable fast correction of the output signal, the sensor can be used in environments with rapidly changing temperature, which is its essential advantage. The paper presents practical implementation of the proposed theoretical aspects and the results of testing the developed sensor.

Keywords: pressure, sensor, non-stationary, temperature.

1. Introduction

Nowadays numerous technical systems need pressure sensors with high accuracy of measurement in environments with rapidly changing non-stationary temperature, such as aerospace systems, scientific research, *etc*. [1–4]. Therefore, development of more advanced sensors and methods of accurate pressure measurement with fast correction of the temperature error is a very important task.

Achievements in microelectronic technology have brought about a large group of piezoresistive sensors designed for different environments [5–9]. Analysis of the characteristics of such sensors suggests their high accuracy, because the temperature error of some types of sensors is equal to fractions of a per cent [7–11]. However, when measuring pressure in environments with rapidly changing temperature (thermal shock, *etc*.), the error can exceed 30% [12, 13].

The current methods [14–18] (such as thermal compensation, cooling method, application of thermal protection films, combined measurement of temperature and pressure, *etc*.) can reduce temperature error. However, when temperature is changing rapidly, the error is significant [12, 13]. In addition, fast correction of errors, which is required for automatic control systems, cannot be performed.

2. Theoretical aspects

Some theoretical aspects for round plates are discussed below [19]. The vertical deflection in the centre of a thin round rigidly restrained plate (Fig. 1) loaded with a pressure p is:

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$$w=\frac{pR^4 12(1-\nu^2)}{64Eh^3}=p\frac{1.66}{\gamma\omega^2}, \tag{1}$$

where: R is a radius of the plate; h is a thickness of the plate; E is the elasticity modulus; ν is the Poisson's ratio; ω is a natural frequency of the round plate; $\gamma=\rho h$; ρ is a density of the plate's material.

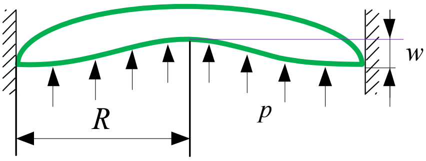

Fig. 1. The vertical deflection of a round plate.

If the plate is loaded with a pressure p and radial forces of compression/tension $\pm N_r$ (Fig. 2), then the vertical deflection in the plate's center is equal to:

$$w=p\frac{1.66}{\gamma\omega^2\pm N_r\frac{10.24}{R^2}}. \tag{2}$$

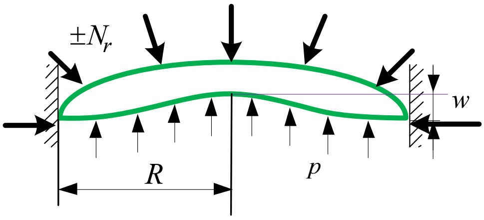

Fig. 2. The vertical deflection of a round plate under radial forces.

Let us assume that we have two thin round restrained plates 1 and 2 (Fig. 3) with identical geometrical parameters and physical characteristics of the materials, except for the coefficient of linear thermal expansion ($\lambda_1<\lambda_2$).

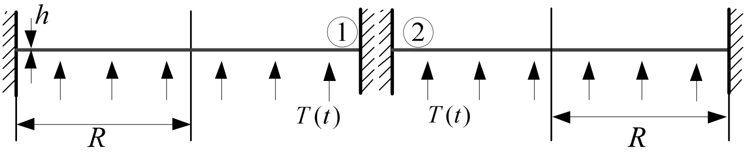

Fig. 3. Identical round plates with different coefficients of linear thermal expansion of materials.

If plates 1 and 2 (Fig. 3) are under influence of a non-stationary temperature, the thermal stress that will arise in them will be expressed as:

$$\sigma_{r1}(z,t)=\sigma_{\varphi 2}(z,t)=\frac{-E\lambda_1}{1-\nu}T(z,t) \tag{3}$$

and

$$\sigma_{r2}(z,t)=\sigma_{\varphi 2}(z,t)=\frac{-E\lambda_2}{1-\nu}T(z,t)\,, \tag{4}$$

where $T(z,t)$ is a temperature field in the body of the plates with their coefficients of linear thermal expansion λ_1 and λ_2.

In the case of restrained plates 1 and 2, the above-mentioned thermal stresses (3) and (4) correspond to the radial forces $\pm N_r$ (Fig. 4) as follows:

$$N_{r1}(t)=\int_0^h \sigma_{r1}(z,t)dz=\frac{\pm E\lambda_1}{1-\nu}\int_0^h T(z,t)dz \tag{5}$$

and

$$N_{r2}(t)=\int_0^h \sigma_{r2}(z,t)dz=\frac{\pm E\lambda_2}{1-\nu}\int_0^h T(z,t)dz\,. \tag{6}$$

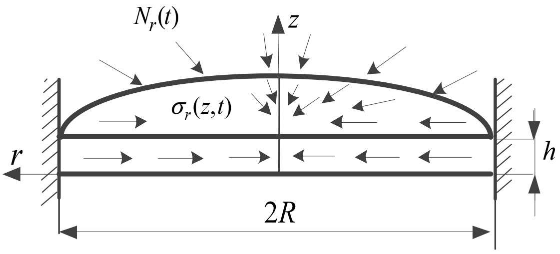

Fig. 4. The thermal stresses and corresponding radial forces.

It is apparent that, as the geometrical parameters and physical properties of the materials of plates 1 and 2 (Fig. 3) are identical, their static and dynamic characteristics in standard conditions will be identical, too. However, under a thermal impact, as it is seen from the obtained (2) – (6), due to the different coefficients of linear thermal expansion, the plates will be exposed to different thermal stresses, which is why their statics and dynamics at measurement of a pressure $p(t)$ will differ.

If plates 1 and 2 are under a pressure p and radial forces $N_{r1}(t)$ and $N_{r2}(t)$, then the vertical deflections in the centre of the plates are:

$$w_1(t)=p_0\frac{1.66}{\gamma\omega^2\pm N_{r1}(t)\dfrac{10.24}{R^2}} \tag{7}$$

and

$$w_2(t)=p_0\frac{1.66}{\gamma\omega^2\pm N_{r2}(t)\dfrac{10.24}{R^2}}\,. \tag{8}$$

Taking into account (5) and (6) will result in the following equations:

$$w_1(t)=p_0\frac{1.66}{\gamma\omega^2\pm\dfrac{10.24}{R^2}\dfrac{E\lambda_1}{1-\nu}\displaystyle\int_0^h T(z,t)dz}\,, \tag{9}$$

$$w_2(t) = p_0 \frac{1.66}{\gamma\omega^2 \pm \frac{10.24}{R^2} \frac{E\lambda_2}{1-\nu} \int_0^h T(z,t)dz}. \tag{10}$$

Solving (9) and (10), we will obtain:

$$p_0(t) = \frac{\gamma\omega^2}{1{,}66} w_1(t)\left[1 \pm \frac{\lambda_1\left(w_2(t) - w_1(t)\right)}{w_1(t)\lambda_1 - w_2(t)\lambda_2}\right]. \tag{11}$$

These are the above-described regularities that underlay the proposed type of pressure sensors and the corresponding method of pressure measurements.

3. Practical implementation of theoretical aspects

Let us use the mentioned plates as diaphragms in a piezo-resistive pressure sensor (Fig. 5). On diaphragms 1 and 2, the identical piezo-resistors 3 and 4 will be set, which at a measured pressure $p(t)$ will produce output signals $U_1(t)$ and $U_2(t)$, respectively.

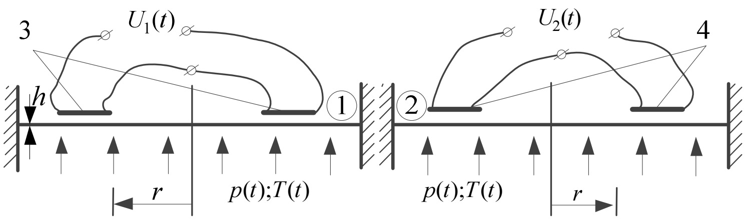

Fig. 5. A piezo-resistive pressure sensor with two diaphragms.

If there is no thermal influence, the output signals from piezo-resistors 3 and 4 will be equal to ($U_1(t) = U_2(t)$), and if the measured pressure $p(t)$ is not changing fast, it can be written that:

$$U_1(t) = U_2(t) = \frac{p(t)}{k}, \tag{12}$$

where k is a static coefficient of sensor transformation, which takes into account the topology of piezo-resistors on diaphragms and their supply voltage.

Thus, in this case the values of the output signals $U_1(t)$ or $U_2(t)$ make it possible to define the value of measured pressure as:

$$p(t) = U_1(t) \times k = U_2(t) \times k\,. \tag{13}$$

If the diaphragms during measurement of the pressure $p(t)$ are under influence of a temperature $T(t)$ (Fig. 5), the obtained values $U_1(t)$ and $U_2(t)$ will differ, since the diaphragms, having different values of coefficients of linear thermal expansion, will be exposed to different thermal stresses. Therefore, the values of measured pressure $p_1(t)$ and $p_2(t)$ determined by the output signals $U_1(t)$ or $U_2(t)$ will also be different:

$$p_1(t) = U_1(t) \times k \neq p_2(t) = U_2(t) \times k\,. \tag{14}$$

On the other hand, using expression (1), we will have:

$$p_1(t)=\frac{w_1(t)\gamma\omega^2}{1.66}, \tag{15}$$

$$p_2(t)=\frac{w_2(t)\gamma\omega^2}{1.66}. \tag{16}$$

Taking into account (14–16), (11) will be written down as follows:

$$p_0(t)=k\cdot U_1(t)\left[1\pm\frac{\lambda_1\big(U_2(t)-U_1(t)\big)}{U_1(t)\lambda_1-U_2(t)\lambda_2}\right]. \tag{17}$$

This equation enables to obtain the true value of measured pressure in an environment with a non-stationary temperature.

If the measured pressure changes quickly, then the output signal of the sensor will also have a dynamic error. Therefore, the first step in the measurement method must be elimination of this error.

The dynamic model of piezo-resistive pressure sensors with a round diaphragm is known to be described by integral Volterra equation:

$$U(t)=k\int_0^t p(\tau)\cdot e^{-\beta(t-\tau)}\cdot\sin(\omega(t-\tau))d\tau\,. \tag{18}$$

Double integration of (18) will result in:

$$p(t)=\frac{\ddot{U}(t)+2\cdot\beta\cdot\dot{U}(t)+(\omega^2+\beta^2)\cdot U(t)}{k\cdot\omega}. \tag{19}$$

Direct implementation of this equation is impossible, since direct differentiation of the output signal is an incorrect procedure. Therefore, application of the known methods of measuring dynamic pressure [20, 21] will result in $p_1(t)$ and $p_2(t)$ for each of the diaphragms. Then, to find the value of measured pressure, (17) will be used, in which the just defined values $p_1(t)$ and $p_2(t)$ are substituted for the values $U_1(t)$ and $U_2(t)$.

The proposed type of piezo-resistive pressure sensor with two diaphragms for environments with a non-stationary temperature is shown in Fig. 6.

The piezo-resistive pressure sensor for environments with a non-stationary temperature (Fig. 6b) consists of a body 4, round diaphragms 1 and 2 rigidly restrained in the body 4, piezo-resistors 3 and 5 located on diaphragms 1 and 2.

The measurement goes through the following stages:

- the piezo-resistive pressure sensor with two diaphragms with identical parameters but with different coefficients of linear thermal expansion perceives the measured pressure $p_0(t)$;
- the output signals $U_1(t)$ and $U_2(t)$ of the sensor are processed using any of the known methods of dynamic pressure measurement [6,7] in order to correct the dynamic error, and the values $p_1(t)$ and $p_2(t)$ are obtained;
- the true value of measured pressure $p_0(t)$ is calculated by (17), in which the defined values $p_1(t)$ and $p_2(t)$ are substituted for $U_1(t)$ and $U_2(t)$, respectively;
- if the pressure is not dynamic, then the values of output signals $U_1(t)$ and $U_2(t)$ of the sensor are directly placed in (17), and the true value of measured pressure $p_0(t)$ is calculated.

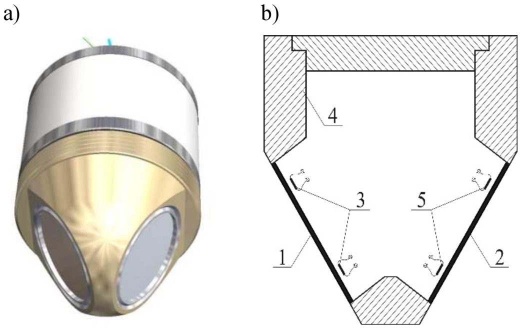

Fig. 6. A piezo-resistive pressure sensor with two diaphragms for environments with a non-stationary temperature (a) and its design (b).

A piezo-resistive pressure sensor for environments with a non-stationary temperature (Fig. 6b) consists of a body 4, round diaphragms 1 and 2 rigidly restrained in the body 4, piezo-resistors 3 and 5 located on diaphragms 1 and 2.

4. Testing the sensor and the corresponding method

The method and the respective sensor were tested in the conditions of simultaneous application of a pressure shock with an amplitude of 0.2 MPa and a thermal shock with an amplitude of 135°C.

The sensor (Fig. 6) had two diaphragms with the radius R = 4 mm, thickness h = 0.21 mm and elasticity modulus $E = 2.1 \cdot 10^{11}\ Pa$, the diaphragms were made of an alloy with different coefficients of linear thermal expansion: $\lambda_1 < \lambda_2$ and the Poisson's ratio $\nu = 0.3$.

When measuring a pressure shock with simultaneous applying a thermal shock, the output signals $\widetilde{U}_1(t)$ and $\widetilde{U}_2(t)$ are obtained (Fig. 7).

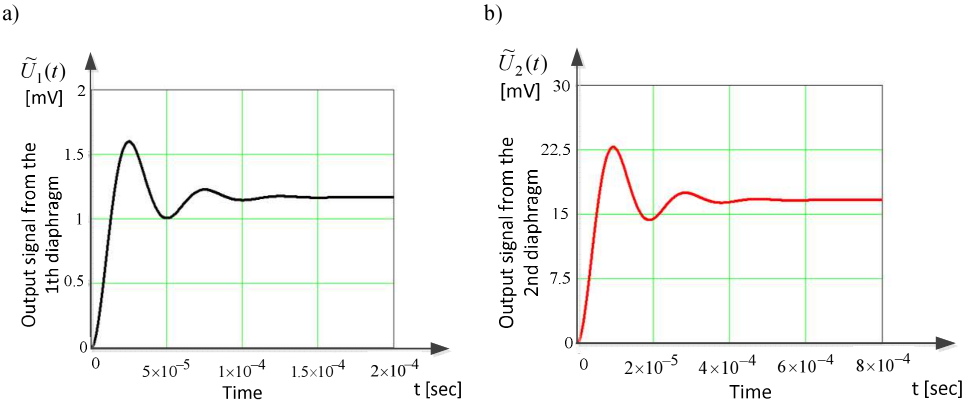

Fig. 7. The output signals of the sensor at measurement under a pressure shock with simultaneous applying a thermal shock: the diaphragm of an alloy with λ_1 (a); the diaphragm of an alloy with λ_2 (b).

Using the dynamic pressure measurement method [20] results in the restored signals $\widetilde{p}_1(t)$ and $\widetilde{p}_2(t)$ (Fig. 8).

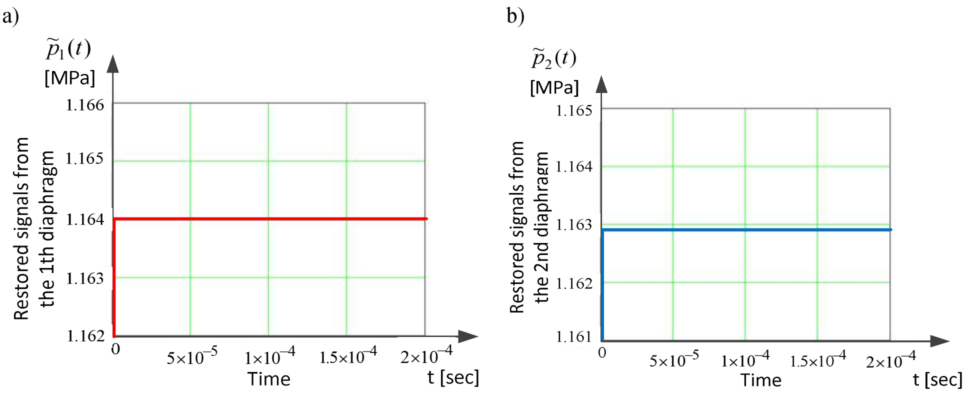

Fig. 8. The restored signals $\tilde{p}_1(t)$ and $\tilde{p}_2(t)$: the diaphragm of an alloy with λ_1 (a); the diaphragm of an alloy with λ_2 (b).

Using (17), we obtained the true value of measured pressure (Fig. 9), and the relative error equalled 2,45%.

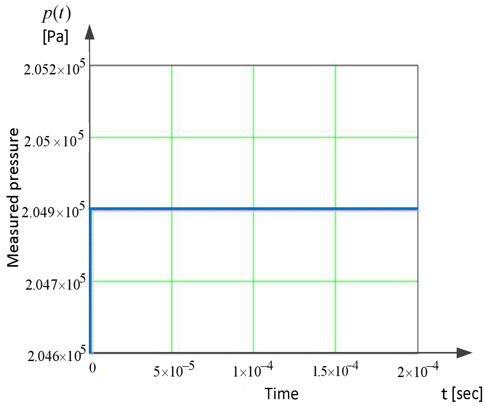

Fig. 9. The true value of measured pressure.

5. Conclusions

Therefore, testing the method and the corresponding sensor gave a quite satisfactory result.

The formula (17) enables to calculate the true values of both dynamic and static pressures of an environment with a non-stationary temperature. Since such a calculation is implemented in the real-time mode due to the simplicity of mathematical procedures, accurate measurement of pressure can be carried out at a rapidly changing ambient temperature. Thus, the proposed type of piezo-resistive pressure sensor with two diaphragms can be used in high-speed control systems. However, a weak point of such sensors is the necessity to ensure identical properties and parameters of the diaphragms.

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