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METROLOGICAL PERFORMANCE OF INTEGRATED MULTIPLE AXIS MEMS ACCELEROMETERS UNDER THERMAL EFFECT

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Abstract – Microelectromechanical system (MEMS) accelerometers are widely used for the measurement of acceleration, tilt, vibration, and shock in moving objects. MEMS-based accelerometers are rather sensitive to the temperature changes. The paper presents the dependence between the temperature changes and metrological performance of MEMS-based accelerometer. Methods of the temperature compensation are considered in this paper.

Keywords: MEMS-based accelerometer, thermal errors, moving mass, temperature sensitivity, elastic suspension.

1. INTRODUCTION

MEMS accelerometers are related to inertial sensors. They are widely used for the measurement of such parameters as acceleration, tilt, vibration, and shock in moving objects [1, 2, 3, 4]. MEMS accelerometers differ from each other by their resolution, absolute accuracy, cumulative error, hysteresis, resistance to vibrations, impacts, and heat. Each accelerometer incorporates a moving mass which performs angular or translational motion relative to its frame. A pendulous accelerometer is characterized by an angular motion of a moving mass, while in an axial accelerometer its motion is translational. MEMS accelerometer can operate both in open-loop and compensation modes [5, 6].

A MEMS accelerometer is a silicon-based capacitive sensor for testing the acceleration of an object along a given axis. The accelerometer principle is to measure the motion of a moving mass and convert it into an electric signal.

MEMS accelerometers are rather sensitive to the temperature changes [7, 8, 9, 10, 11]. The stiffness of the elastic suspension is changed with temperature, and the scaling factor of a sensor is changed also. The change of electrode sizes results in a change of capacities. Moreover, a zero shift is observed caused by a drift of both micromechanical and electronic components of the accelerometer system. In order to achieve the maximum measurement accuracy, these changes should be taken into account.

One of the current directions of the research to improve micromechanical sensors is measurement along several axes. This allows significant improvement of the user interface and information system on the whole.

2. STRUCTURE AND PHYSICAL PRINCIPLE

A three-axial accelerometer the structure of which is given in Fig. 1 is used in this experiment. This accelerometer incorporates the moving mass suspended in the frame by means of the elastic suspension. The motion of the moving mass caused by the acceleration along *Z* axis is measured by planar electrodes, one of which is the moving mass. The second electrode is sprayed on a glass support placed under the moving mass. The third electrode is located on the upper cover.

The frame is mounted to the glass support by the two-axis elastic suspension. The frame displacements caused by the acceleration along *X* and *Y* axes are measured by interdigitated electrode structures. Terminal areas are intended for the connection between the sensor and the electronic component of the accelerator.

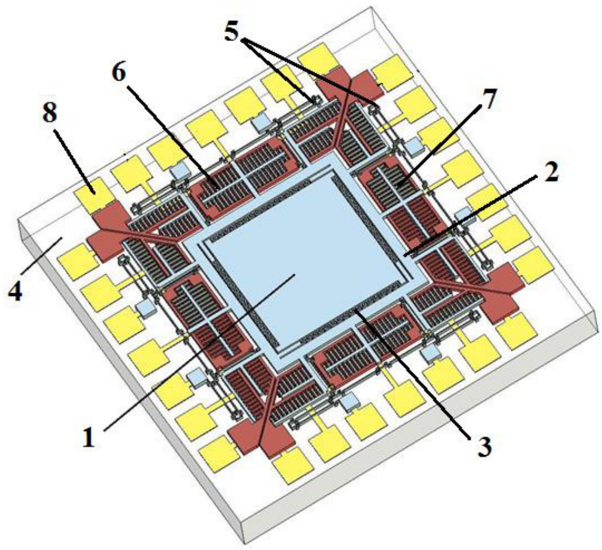


Fig. 1. Schematic drawing of silicon sensor

1 - moving mass; *2* – frame; *3* – elastic suspension; *4* – glass support; *5* - two-axis elastic suspension; *6, 7*– interdigitated electrode structures; *8* – terminal areas.

The design feature is that the sensor has an elastic suspension, which is sensitive along the axes X and Y at the same time; therefore, the rigidity of the two axes should be identical. Elastic suspensions microaccelerometer have one common property - is contradictoriness requirements for their behavior.

For example, preparation of suspensions with low stiffness whiles simultaneously their identity and reliability is one of the most difficult technical problems. The most important task is varying the geometric parameters of the elastic suspensions to determine the geometric dimensions, which will provide a specified range of the eigenfrequencies of the accelerometer sensor.

2.1 The elastic suspension of the sensor along the Z axis

Development of the construction begins with the development of internal suspension, sensitive along the Z axis, Fig. 2.

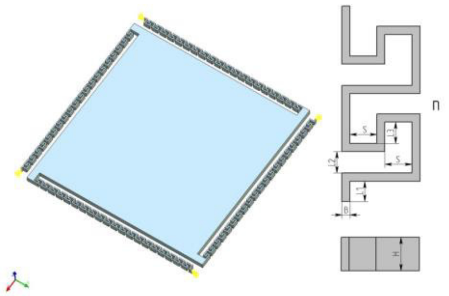
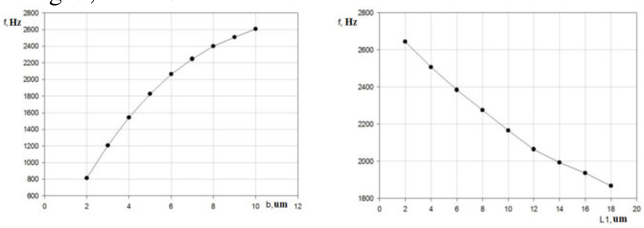


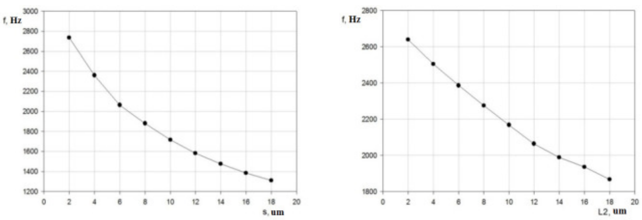
Fig. 2. Suspension sensitive along the Z axis

Dependence eigenfrequency of the sensor along the Z axis from the geometrical parameters of torsions are shown in Fig. 3, 4 and 5.



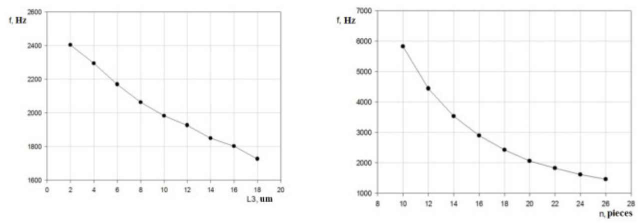
a) Torsion thickness is b b) Torsion length is L1

Fig. 3. Dependence eigenfrequency of the sensor from torsion parameters



a) torsion width is s b) torsion length is L2

Fig. 4. Dependence eigenfrequency of the sensor from torsion parameters



a) torsion width is L3 б) segments number is n

Fig. 4. Dependence eigenfrequency of the sensor from torsion parameters

Data characterizing the change the eigenfrequency of the torsion when change of its geometrical parameters at the unit shown in Fig. 6.

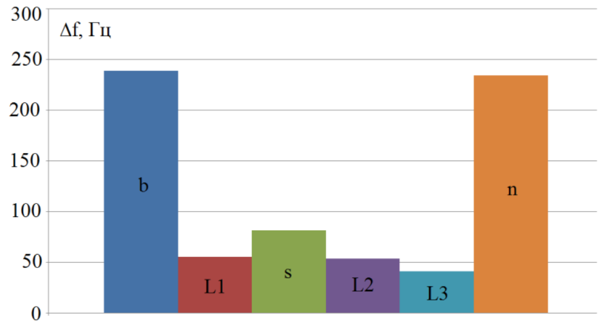


Fig. 6. Change the eigenfrequencies of the sensor by change of geometrical parameters of the torsion at the unit.

The eigenfrequencies of the sensor to a change the thickness of the torsion and the number of segments are most sensitive. Parameter L3 has the lowest sensitivity.

2.2 The elastic suspension of the sensor along the X and Y axes

The design of the torsions, the sensitive along the axes X and Y is shown in Fig. 7.

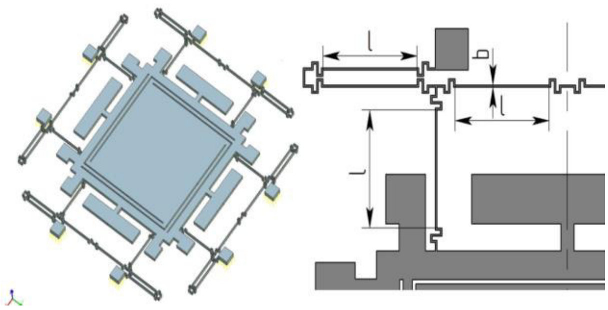
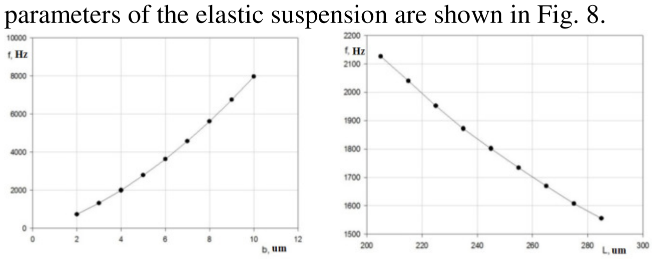


Fig. 7. Torsions the sensitive along the axes X and Y

In order to the torsions had a sensitivity biaxially simultaneously is necessary to observe the torsions equal lengths, as shown in Fig. 7. Therefore, under this condition the analysis was conducted. Thus, on the eigenfrequences of the sensor is influenced only two torsion parameters are their thickness and length. Changes eigenfrequencies of the accelerometer sensor as a function of the geometric parameters of the elastic suspension are shown in Fig. 8.



a) Torsion thickness is b b) Torsion length is L

Fig. 8. Dependence eigenfrequency of the sensor from torsions parameters

On the eigenfrequencies the thickness of the torsions b makes the greatest influence.

These dependences allow choosing the geometric parameters of elastic suspension so as to achieve a provided frequency properties of the accelerometer.

Sensor parameters have been selected so that its eigenfrequencies in all axes are closely spaced, Fig. 9.

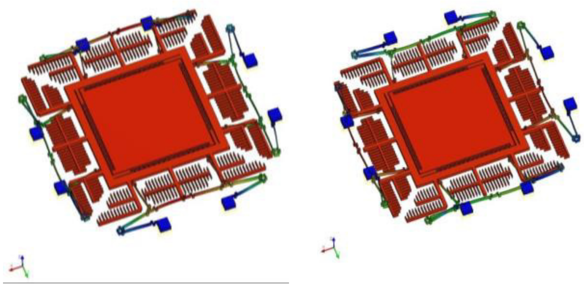


Fig. 9. Sensor frequency modes of the accelerometer

All the others the eigenfrequencies of sensor lie above the first three modes of oscillations.

3. TEMPERATURE PERTURBATIONS IN MEMS ACCELEROMETER

The operational temperatures in MEMS accelerometer range from –40^{0}C to +110^{0}C that results in a change of scaling factors of sensors. This leads to the change in the eigenfrequency sensor and consequence is change in the mechanical scale factors of the accelerometer sensor, Fig. 10.

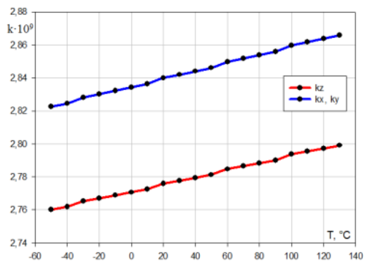


Fig. 10. Changes the transmission coefficients from temperature

Approximating functions of charts are presented below.

$$k_{x,y}(T) = 2{,}8346 \cdot 10^{-9} + 2{,}4309 \cdot 10^{-13} \cdot T,$$

$$k_z(T) = 2{,}7710 \cdot 10^{-9} + 2{,}1822 \cdot 10^{-13} \cdot T.$$

The dependence between the temperature and scaling factor of the sensor is shown in Fig. 11.

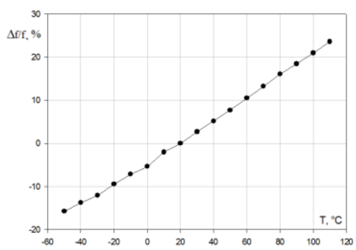


Fig. 11. Relative change of scaling factor depending on temperature

Variations of the environment temperature provide thermal noise generated by the micromechanical and electronic components of the accelerometer. Thermal vibrations generated by the sensor due to its low weight also contribute to the general level of noise. Moreover, the random motion of the electric current carriers can be observed in conductor or semiconductor devices.

Noise has a spectral density. In case of the uniform distribution from 0 Hz to resonant frequency of noise generation, the root mean square (RMS) value of spectral density of noise within the frequency range is considerably lower than that of the resonant frequency and can be obtained from [12]

$$\bar{F}_n = \sqrt{4 k_b T \gamma} \qquad (1)$$

where k_b = 1,38 · 10^{-23}J/k is Boltzmann constant, $\gamma = \frac{m\omega_0}{Q}$, T is the temperature; Q is the quality factor of sensor; m is the mass; ω_0 is the resonant frequency. The schematic structure of the sensor in presence of thermal noise generated by the micromechanical component of the accelerometer is shown in Fig. 12.

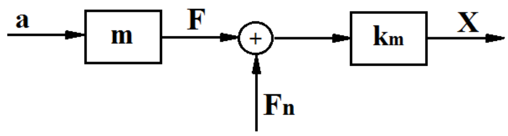


Fig. 12. Schematic structure of sensor

Where k_m is scaling factor and x is movement of the moving mass.

From the condition of equality between thermal noise and vibrational energies [12] obtain the equivalent noise acceleration:

$$\bar{a}_n = \frac{\bar{F}_n}{m} = \frac{\sqrt{4 k_b T \gamma}}{m} = \sqrt{\frac{4 k_b T \omega_0(T)}{mQ}}. \qquad (2)$$

Equation (2) determines the threshold sensitivity, i.e. the minimum signal to be possibly measured.

Fig. 13 and 14 show the dependencies between the equivalent noise acceleration and the temperature for the accelerometer structure suggested in this paper.

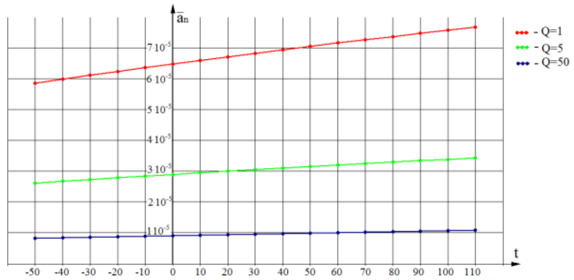


Fig. 13. Equivalent noise acceleration and the temperature dependence by axes X and Y

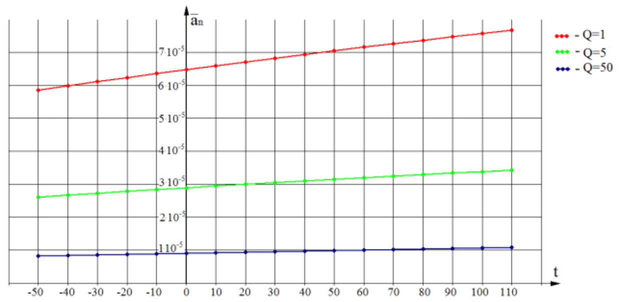


Fig. 14. Equivalent noise acceleration and the temperature dependence by axis *Z*

The signal-noise ratio can be increased owing to the increase of mass and quality factor, and the decrease of resonant frequency. In the open-loop mode, the increase of the quality factor can result in a too strong noise at the resonant frequency [12]. The increase of the quality factor does not lead to the decrease of the total noise energy, however, concentrates it nearby the resonant frequency, thereby decreasing the noise level in the frequency range below the resonant.

The general level of noise is also affected by the operating frequency band. The RMS value of noise generated by the micromechanical component $\bar{a}_{rs}$ depends on the noise spectral density $\bar{a}_n$:

$$\bar{a}_{rs} = \bar{a}_n \sqrt{\Delta f}, \qquad (3)$$

where Δf is the operating frequency band; $\bar{a}_{rs}$ is the RMS value of noise; $\bar{a}_n$ is the spectral density of noise.

Thermal noises are also present in a capacitance bridge circuit and can be mostly determined by their voltage:

$$U_n = k_b T \pi C(T), \qquad (4)$$

where *C(T)* is the capacity between the electrodes of the displacement sensor. Thermal noise voltage is a zero-level error. This error can be reduced by the temperature control for the sensor or the capacity increase of the displacement sensor. The latter is more applicable to MEMS accelerometers.

The increase of capacity between the electrodes of the displacement sensor can be achieved either by the decrease of the gap between the movable and stationary conductive electrodes or the increase of the contact area of electrodes, or by the both ways at a time. The gap is selected accounting for the technological capability of manufacturing. Interdigitated electrode structures are used to increase the capacity of the displacement sensor**.**

4. COMPENSATION METHODS FOR THERMAL EFFECTS

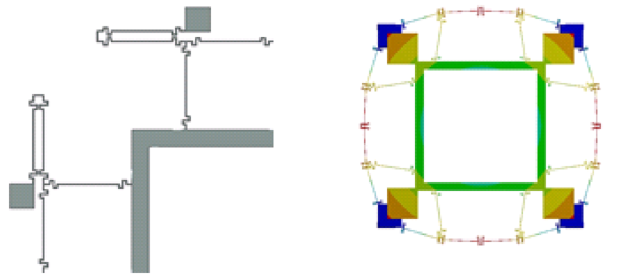
Thermal effect compensation can be achieved by the structural and circuit design.

4.1. Structural design

The temperature has the greatest effect on the elastic suspension of accelerometers. Therefore, errors produced by the temperature changes can be minimized by the structural modification of the torsion suspension.

In order to decrease the internal stresses, the structure of the torsion suspension must be supplemented with compensator springs which deform at widening of torsions resulting in the decrease of the internal stresses.

The torsion suspension with compensators is shown in Fig. 15.



a – structure *b* – deformation at + 105°C

Fig. 15. Schematic drawing of temperature tolerant elastic suspension

Due to the introduction of several compensators in the torsional suspension, the temperature effect on the eigenfrequency does not exceed 0,4 %. The temperature effect on the scaling factor of the sensor is reduced by tens of times and makes shares of percent, Fig. 16.

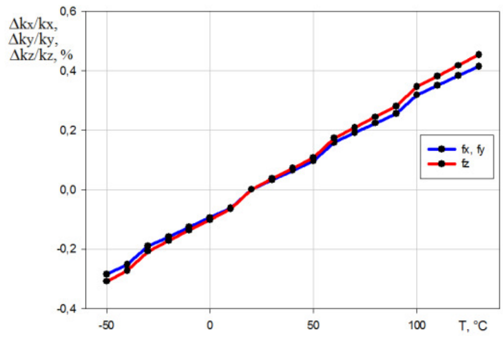


Fig. 16. Relative change of scaling factor depending on temperature

The suggested elastic suspension allowed the authors to manufacture two- and three-axis test accelerometers. The temperature tolerant suspension by axis *Z* is shown in Fig. 17.

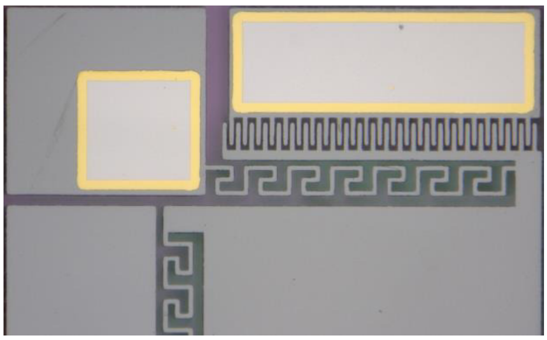


Fig. 17. Temperature tolerant suspension by axis *Z*

4.2. Circuit design

The temperature dependence of the scaling factor can be compensated by the circuit design which implies the use of a microcontroller.

This problem can be also solved by embedding the temperature sensor that simplifies the circuit design. The structure of the suggested accelerometer contains correcting electrodes that can be used for self-calibration at temperature measurements.

At applying the constant voltage to electrodes, the electrostatic adhesion force generated between them equals to a certain external force or acceleration:

$$F_k = -\frac{\varepsilon\varepsilon_0 S}{2d^2}U^2, \qquad (5)$$

where U is the constant voltage; F is the electrostatic adhesion force; d is the distance between electrodes; ε is the absolute dielectric constant; S is the contact area of electrodes. The applied voltage is usually stabilized and weakly depends on temperature. The idea of self-calibration is that that the output signals generated by the accelerometer depend on the acceleration and the calibrating voltage and are changed proportionally because both of them equally depend on the stiffness of the elastic suspension which, in turn, depends on the temperature changes.

CONCLUSIONS

The three-axis accelerometer was designed. The temperature changes resulted in a change of the scaling factor of the accelerometer sensor.

The reduction of the temperature effect on the scaling factor of the sensor was provided by the temperature tolerant elastic suspensions introduced in the structure and the correction of eigenfrequency of the sensor. As a result, the temperature sensitivity of the accelerometer sensor was less than 1% across the whole temperature range.

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