Development of MEMS-Accelerometer Capacitive Sensitive Element with a Variable Acceleration Range up to 20000g

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Abstract — **One of the problems of MEMS-accelerometers is a small nomenclature of ranges for very large accelerations (about 20000g and more). This is explained by the fact that the development and manufacturing of sensors for such ranges is very difficult task. Construction of the sensitive element have to be soft, capable of measuring accelerations from units (g) to tens of thousands (g), and at the same time rigid enough to provide resistance to long-term shock impacts of high intensity, which is the main problem in the development of MEMS-accelerometers for very large ranges. In addition, the application field of such accelerometers is quite specific, therefore sensitive elements should be resistant to various vibrations, as well as high temperatures.**

Keywords—MEMS; accelerometers; sensitive element; acceleration

I. INTRODUCTION

The main element of MEMS systems is the electromechanical energy converter. Such transformers can be based on various physical principles: electromagnetic, piezoelectric, capacitive (electrostatic). Preference is given to the latter as the most technologically advanced [1-2].

II. RESULTS AND DISCUSSIONS

Within the framework of this work, a sensitive element (SE) of the MEMS accelerometer of the comb type is developed, which operates according to the following principle, the displacement of the inertial mass is recorded through a change in the capacitance of two "parallel plates" of the electrodes [3]. One of them is a movable (rotor), with a given mass, another stationary (stator). A differential capacitive readout circuit is formed in the SE: the capacitance is calculated relative to both sides of the moving part (inertial mass), when it is displaced, the capacitance of one capacitor decreases and at the same time the capacity of the other increases, which ensures linearity of the output signal and compensates drifts. In other words, under the action of acceleration on the SE design along its sensitivity axis, the inertial mass shifts, which disbalances the differential capacitor, causing a voltage change at the output, whose amplitude is proportional to the acceleration.

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To model the static characteristic of the transformation "measured linear acceleration - deformation", a solid model was created for the range of acceleration ±20000g, presented in Figure 1.

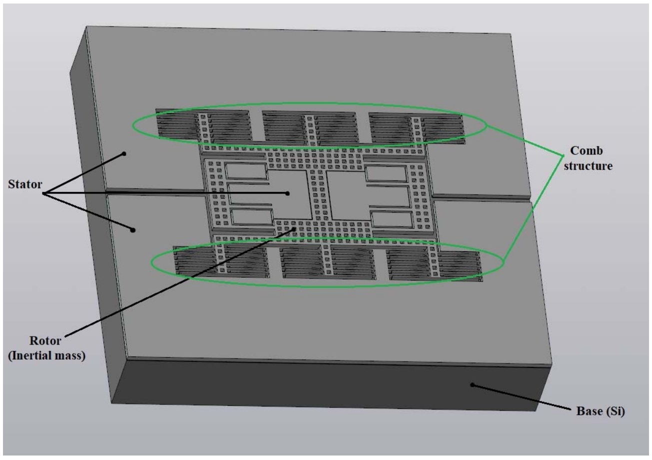

Fig.1 Model of sensitive element MEMS accelerometer

Further, to simplify the calculations with the help of specialized CAD, the SE model of the MEMS accelerometer was simplified. From the model, structural elements that do not affect its mechanical work were excluded. For the modeling process, only the working layer (inertial mass, stator) was left, since this significantly reduces the simulation time and does not affect the reliable result.

The results of calculating the design of the SE, in addition to the maximum and minimum values of the deformation, of course, also contain intermediate values that are obtained by parametric analysis and with which a relationship is established between the applied linear acceleration and the deformation of the movable part of the SE at any point of the structure - in Figure 2 as The example shows the simulation result with acceleration equal to 200000 m/s^2.

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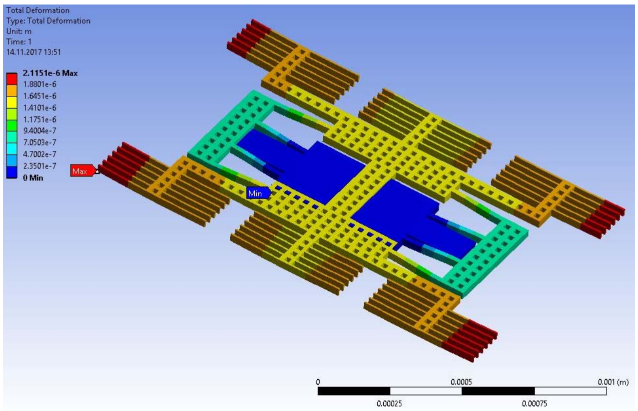

Fig.2 Acceleration action on the sensitive element model MEMS accelerometer

The overall results of the SE MEMS accelerometer simulations for all points were summarized in Table 1, where each line contains information on the magnitude of the maximum strain for each value of the applied linear acceleration.

This result is very important, since the value of the "deformation" of the comb fingers constituting the electrical capacitance between the stator and the rotor is of particular interest. And the character of the capacitance behavior, namely, the scale factor and nonlinearity, will determine the output parameters of the MEMS accelerometer.

TABLE I. STATIC CHARACTERISTIC OF THE TRANSFORMATION "MEASURED LINEAR ACCELERATION - DEFORMATION" FOR SE MEMS ACCELEROMETER

Acceleration, m/s²	**Deformation, µm**
20000	0.199
40000	0.385
60000	0.567
80000	0.723
100000	0.990
120000	1.153
140000	1.368
160000	1.542
180000	1.798
200000	1.968

Now we approximate the dependence of the maximum deformation on the applied acceleration with the help of a polynomial of the first degree, the expression 1:

$$def = p_1 \cdot a + p_2 \tag{1}$$

where:

p1 and p2 – of the polynomial coefficient;

def – magnitude of maximum deformation, (µm);

a – the magnitude of the applied acceleration, (g).

The coefficients of the polynomial for the SE MEMS accelerometer 20000g are:

$p1 = -9.517 \cdot 10^{-4}$ $p2 = -1.333 \cdot 10^{-4}$

To evaluate the correctness of the choice of the type of the approximating function, we calculate the value of the maximum relative error of approximation according to the expression 2:

$$error = \max\left(\frac{def_{\text{mod}} - def_{app}}{diap \cdot def_{app}} \cdot 100\%\right) \tag{2}$$

where:

def_{mod} – the value of the maximum deformation from the table 1;

def_{app} – the value of the maximum deformation obtained from the results of approximation;

$diap$ – range of measured accelerations.

The magnitude of the maximum relative error of approximation for the SE MEMS accelerometer 20000g is 0.031%.

All these results are negligibly small, from which it can be concluded that the form of the function chosen for approximation (a polynomial of the first degree) is chosen, true.

The gap between the "fingers" of the stator and the rotor is for this type of construction d_1 = 3 µm, d_2 = 12 µm. To calculate the resultant gap between the stator and the rotor ("fingers") of the SE structure with the known acceleration, it is necessary to add or subtract the strain value given in Table 1 to the nominal gaps d_1 = 3 µm, d_2 = 12 µm. This will calculate the value of the electrical capacitance "fingers" of the comb SE and obtain a static characteristic "measured linear acceleration - electrical capacitance".

We calculate the electric capacity formed by the "fingers" of the comb:

In the absence of external acceleration, the capacitances will be, expression 3 [4]:

$$C_0 = \frac{\varepsilon_0 \cdot \mathrm{N} \cdot L \cdot t}{d_0}. \tag{3}$$

where:

$\varepsilon_0 = 8.85 \cdot 10^{-12} F \cdot m^{-1}$ - dielectric constant;

N - number of containers formed by fixed and movable combs (42);

L - comb length (195 um);

t - thickness of the comb (20 um);

d0 - gap between the combs.

When there is an acceleration directed along the measuring axis, the distance between the combs changes by an amount x, and, consequently, of the capacitance, expression 4:

$$C_1 = \frac{\varepsilon \cdot N \cdot L \cdot t}{4 - x} + \frac{\varepsilon \cdot N \cdot L \cdot t}{12 + x};$$
$$C_2 = \frac{\varepsilon \cdot N \cdot L \cdot t}{4 + x} + \frac{\varepsilon \cdot N \cdot L \cdot t}{12 - x}. \quad (4)$$

Then the difference of capacities will be, expression 5:

$$\Delta C = C_1 - C_2. \quad (5)$$

Using the given calculated relations and the initial data, we obtain the static characteristic of the transformation "measured linear acceleration - electrical capacitance", table 2.

TABLE II. STATIC CHARACTERISTIC OF THE TRANSFORMATION "MEASURED LINEAR ACCELERATION - ELECTRICAL CAPACITANCE" FOR THE SE MEMS ACCELEROMETER

Measured linear acceleration, g	**Electrical capacitance C_1, pF**	**Electrical capacitance C_2, pF**
0	0,5759	0,5759
2000	0,5748	0,5979
4000	0,5646	0,6111
6000	0,5552	0,6254
8000	0,5464	0,6413
10000	0,5384	0,6582
12000	0,5310	0,6771
14000	0,5241	0,6979
16000	0,5177	0,7210
18000	0,5119	0,7466
20000	0,5066	0,7752

We approximate the obtained dependence of the capacitances C_1 and C_2 on the applied acceleration by the polynomial of the second degree, expression 6:

$$C_{1,2} = p_1 \cdot a^2 + p_2 \cdot a + p_3 \quad (6)$$

where:

p1, p2 and p3 – of the polynomial coefficient;

a – applied acceleration, (g);

C1,2 – one of the capacitances of SE MEMS accelerometer, (pF).

Thus, the behavioral model for the SE MEMS accelerometer in the form of the dependence of the capacitances C1 and C2 on the measured acceleration can be described by the following functional dependence, expressions 7, 8:

$$C_1 = 1.382 \cdot 10^{-8} \cdot a^2 - 7.328 \cdot 10^{-5} \cdot a + 0.576 \quad (7)$$

$$C_2 = 3.968 \cdot 10^{-8} \cdot a^2 - 6.482 \cdot 10^{-5} \cdot a + 0.576 \quad (8)$$

Since the measurement of one of the capacitances C_1 or C_2 (directly) leads to the appearance of a large nonlinearity. For this reason, the MEMS accelerometer electronic system performs the transformation of the form "capacitance-voltage" not directly, but according to expression 9:

$$U_{вых} = K \cdot \frac{C_2 - C_1}{C_2 + C_1} \cdot U_{REF} + U_0 \quad (9)$$

where:

K – scale MEMS accelerometer coefficient, V/g

U_0 – zero offset MEMS accelerometer, V

U_{REF} – reference voltage MEMS accelerometer (+2,3 V)

Therefore, in order to estimate the scale factor and the nonlinearity of the transformation "measured linear acceleration - electric capacitance" $U_{REF} \cdot (C_2 - C_1)/(C_2 + C_1)$ from the applied linear acceleration. The results of the calculation for the SE MEMS accelerometer are shown in Table 3.

TABLE III. STATIC CHARACTERISTIC OF THE TRANSFORMATION "MEASURED LINEAR ACCELERATION - ELECTRICAL CAPACITANCE" FOR SE MEMS ACCELEROMETER

Acceleration, m/s²	$\frac{C_1 - C_2}{C_1 + C_2} \cdot U_{REF}$ **, V**
0	0
2000	-0,0453
4000	-0,0910
6000	-0,1368
8000	-0,1838
10000	-0,2303
12000	-0,2781
14000	-0,3271
16000	-0,3775
18000	-0,4289
20000	-0,4820

Accordingly, the scale factor of the SE MEMS accelerometer was -723 uV/g.

The nonlinearity of the transformation "measured linear acceleration - electrical capacitance" will be evaluated as the value of the maximum relative deviation of the calculated value from Table 3 from the corresponding value obtained by approximation by a linear function, expression 10:

$$nonlinearity = \max\left(\frac{CD_{\text{mod}} - CD_{app}}{diap \cdot CD_{app}} \cdot 100\%\right) \quad (10)$$

where:

CD_{mod} – the value of the reduced differential capacitance $U_{REF} \cdot (C_2 - C_1)/(C_2 + C_1)$ from table 3;

CD_{app} – the value of the reduced differential capacitance $U_{REF} \cdot (C_2 - C_1)/(C_2 + C_1)$, obtained by approximation by a linear function;

$diap$ – range of measured accelerations.

III. CONCLUSIONS

Accordingly, the nonlinearity of the conversion "measured linear acceleration - electrical capacitance" of the SE MEMS accelerometer was 1%.

REFERENCES

[1] Nanotechnology in Electronics. Ed. Y.A. Chaplygin. Issue 3. Moscow: Technosphere, 2015, 480 p.

[2] Nanotechnology in Electronics. Ed. Y.A. Chaplygin. Issue 2. Moscow: Technosphere, 2013, 688 p.

[3] A. Shalimov, S.Timoshenkov, N. Korobova, M. Golovinskiy, A. Timoshenkov, E. Zuev, S. Berezueva, A. Kosolapov, "Comb structure analysis of the capacitive sensitive element in MEMS – accelerometer"/ Proceedings SPIE. Int, Soc. for Opt. Eng. January 2015, 9467, 94672W

[4] M., Golovinskiy, M., Oksina., A., Shalimov, Development of MEMS – capacitive sensitive electron accelerometer comb structure. Scientific forum, 2015, №8, 15-22.