Performance-increasing technique in micromechanical accelerometer development

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Abstract. Requirements for higher-performance on-board control systems and instruments applied in a variety of small-scale moving objects results in the necessity to develop micromechanical sensors – small, lightweight, energy-efficient and, at the same time, offering high-reliability performance and easy-to-use. Development of such MEMS will require – in its turn – controlling parameters which determine the quality of the sensor. These strictly-controlled parameters will most immediately influence the desired outcomes and underline more efficient use of resources to achieve the desired aims. The problem discussed has already been studied by many scientists. MEMS have been and are being developed by both Russia-based and foreign companies like Honeywell International Inc., Analog Devices Inc., JSC Radar MMS, Temp-Avia plc., to name a few.

Currently the algorithm of performance-controlling techniques applied to improve performance of MEMS accelerometers pre-production processes has been developed. The algorithm mentioned is realized at the technological level of organizational management and control and as such is used as a supplement to quality control practices and procedures (figure 1). Such combined technique allows for improved efficiency of pre-production processes based on the flexibility of parameter setting and adjustment and improved control over the MEMS element. It also allows for lower production costs and advanced technologies application due to elimination of sensor ageing and higher performance characteristics resulting from the fact that such production technologies make vacuuming of the device inner volume unnecessary while allowing to set the MEMS initial parameters as required for each particular application and sensor.

The detailed description of the algorithm is given in figure 2. The algorithm is implemented in the following way: technological solutions in the technological database are analyzed in terms of compliance with the specification provided by the customer; the analysis performed allows identifying the components and justifying their identification and characteristics; the following stages are mathematical modeling, calculation of phase-amplitude parameters, and simulation modeling. The principal link in this chain is the block of increasing MEMS performance which accounts for parameters to determine both the quality of the sample and the efficiency of the production stage (stiffness coefficient, damping ratio, sensor forces-related parameters). If the parameters calculated do not comply with the specification provided, a new component base (CB) is developed to provide for the parameters required by specification.
Figure 1. Improved performance techniques in pre-production processes

Detailed evaluation of the performance-increasing block will require successive evaluation of the proof-mass stiffness parameters, damping parameters and the force sensor parameters.

In the auto-oscillating micromechanical accelerometer (AMMA) described in the paper the inertial mass is to be limited in motion by OX axis [2].

Constant cross-section beam deformation

\[
\delta(x) = \frac{i^3 F}{6E} \left(3 - \frac{x}{l}\right) \left(\frac{x}{l}\right)^2,
\]

where \(x\) is current coordinate, \(F\) is force, \(l\) is proof-mass thickness, \(J\) is moment of inertia, \(J = \frac{hb^3}{12}\).

Under the condition of the cross-section variable in one of the beam sections the moment of inertia is calculated by integrals with the cross-section of beam \(b\) twice less \(E = 2,1\cdot10^{10}\) Pa is silicon stiffness module.

On the other hand

\[
\delta(x) = ma/c_x.
\]

Evaluation of stiffness coefficient will involve calculation of three values: viscosity friction, eddy-currents in the gap and electro-magnetic current.

The damping ratio is calculated by the below equation

\[
\mu = \mu_0(\frac{\nu}{f} + 2\chi),
\]

where \(\nu = \frac{f}{f_0}\) is relative frequency of proof-mass periodic displacement, \(\chi = \frac{\Delta V}{V}\) is relative speed increment, \(\mu_0\) is relative damping moment under frequency \(f_0\).

Damping ratio [3]

\[
\mu = \mu_0\nu_f
\]

For flat gaps [3]:

\[
\mu_0 = \mu_0^u + \mu_0^f,
\]

where \(\mu_0^u = 2\pi\eta \frac{hr_1^3}{\delta}, \mu_0^f = 2\pi\eta \left(\frac{r_1^2}{4\delta} + \frac{\delta r_1^2}{6}\right), [10]

\mu_0^u, \mu_0^f\) is cylindrical and flat gap damping ratios, \(\eta\) is gas (liquid) viscosity, \(h\) and \(r_1\) is cylinder length and radius, \(\delta\) is clearance measurement, \(r_1\) is cylinder contact surface radius.

Electro-magnetic damping

\[
\mu_0'' = \frac{B_m S_0}{R_{\kappa,\lambda}}.
\]
where $S_a$ is winding loop square, $R_{e,z}$ is shorted winding resistance, $B_a$ is gap induction. [3]

Eddy-current damping

$$
\mu_{e,r} = \frac{k_\mu \rho y (L \gamma)^2 2d_4}{(2d_1 - d_3)d_2},
$$

where $\Phi = LI$ stands for the coil magnetic flux, $\rho$ is coating conductivity, $d_1$ is the gap between magnetic elements, $d_2$ is coil width, $p$ is the number of coils, $y$ is coating thickness.

**Figure 2. Increased performance technique algorithm**

Damping parameters will determine the vacuuming requirements. Considering projected dimensions of the sensor sensing element of 4-5 mm on each side and the full dimensions of the silicon wafer (of 300 mkm in thickness approximately) its mass will exceed the MEMS accelerometer standard values, which means vacuuming is not a critical requirement. The force-related parameters of the magneto-electric converter will sufficiently exceed its electro-static parameters where vacuuming is used to improve reliability of oscillatory system while auto-oscillation modes implemented and improved power parameters of the sensor make this stage in production unnecessary thus allowing for savings of time and money.

The final stage in the block is force parameters evaluation and control.

Gap conductivity calculation
where \( \mu_0 \) is magnet constant; \( l \) is length of the magnetic coating working section (making 0.75 of the plate); \( \Delta \) is gap between the magnet element and the inertial mass surface; \( \mu \) is absolute permeability.

Measurements in simulation procedure (figure 3) allow calculation of the gap induction values.

By Ampere law, the forces in the clearance between the cover and the inertial mass surface will determine the force parameters of the sensor.

**Figure 3.** Magnetic field power lines distribution in the cover and the inertial mass.

Such approach allows choosing geometry and dimensions as well as the sensor elements to suit the specification provided by the customer while improving sensor performance by flexible parameter settings.

Introduction of the performance control block allows to determine the relation of performance parameters to evaluation criteria which are the following: the sensing element as the basis for auto-oscillating micromechanical accelerometer (AMMA) converts the measured input value \( y_{\text{ax}}(t) \) into the measured output signal \( U(t) \). This allows the function \( U = \Phi(y) \). Further the moving link oscillation center displacement is calculated by the following formula

\[
\chi^0 = \frac{k_{\text{III}}y_{\text{ax}} + k_{\text{III}}k_{\text{III}}k_{\text{DC}}x_0}{1 - k_{\text{III}}k_{\text{DC}}},
\]

where \( k_{\text{III}} = F_{\text{ax}}/y_{\text{ax}} \) is primary converter conversion ratio; \( F_{\text{ax}} \) is input force, \( k_b = \frac{2U_{\text{dc}}}{\pi A(1-\frac{\gamma^2}{2})} \) is ratio determined by the non-linearity ratio; \( A \) is sensing element oscillation ratio; \( k_{\text{III}} = 1/c_{\text{e}} \) is rate of conversion; \( F_{\text{DC}} = k_{\text{DC}}U_{\text{cp}} \) is force generated by the force sensor; \( k_{\text{DC}} \) is force sensor rate of conversion; \( U_{\text{cp}} = U_0 \frac{\tau_1-\tau_2}{T_0} \), where \( U_0 \) is supply voltage; \( T_0 \) is period of auto-oscillation; \( \tau_1 \) and \( \tau_2 \) are periods of count pulses.

Instability of the conversion rate is calculated by \( \delta k_\Sigma = \frac{\delta k_\Sigma}{\delta U_0} \Delta U_0 + \frac{\delta k_\Sigma}{\delta T_0} \Delta T_0 \).

Relative instability \( \delta k_\Sigma \) can be seen as \( \delta k_\Sigma = \sqrt{\delta U_0^2 + \delta T_0^2} \).

In auto-oscillating micromechanical accelerometer (AMMA) the minimum value if the input force will be determined in the following way

\[
y_{\text{min}} = \frac{k_{\text{DC}}U_0}{k_{\text{III}}T_0} (\tau_1 - \tau_2)_{\text{min}},
\]

The measurement range applied is \( D = \frac{y_{\text{max}}}{y_{\text{min}}} \) where \( y_{\text{max}} = \frac{k_{\text{DC}}U_0X}{k_{\text{III}}} \), \( X = \frac{\tau_1}{\tau_0} \) is accelerometer output signal modulation.

Table 1 below presents the comparative analysis [4-11] of existing micromechanical sensors.

| Parameter                  | Hybrid accelerometers | MEMS accelerometers | AMMA [11] |
|----------------------------|------------------------|---------------------|-----------|
| Unstable zero shift mg/KC  | 200                    | 100                 | 74        |
|                            | 1[5]                   | 2[6]                | 3[7]      |
|                            | 4[8]                   | 5[9]                | 6[10]     |
Unstable scale ratio ppm/°C  75  180  110  100  = 0
Change range, g  ±4.5  ±30  ±50  ±1.2  ±15  ±0.5  ±24
Dimensions, mm  20  20  34  7.8  4-6  2.25  7.5

The technique presented above allows increased efficiency of pre-production procedures and processes by monitoring the sensor operation and flexibility settings and parameters adjustment based on recurrence and logic of the process resulting from mathematical modeling and simulation modeling. The technique presented is aimed at establishing high-quality products providing for competitive edge for producers of modern micromechanical inertial sensors in Russia.

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