Development of Behavioral Model of Mechanical Module of Integrated Angular Velocity Microsensor using Verilog-AMS

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Abstract - **In the paper, Verilog-AMS behavioral model of the mechanical module of the integrated angular velocity microsensor for the schematic level of MEMS design has been developed. The developed model allows to simulate capacitance changes, output voltages and currents depending on the applied angular velocity and also to perform the analysis of the device at the schematic design level.**

Keywords - **Micro-Electro-Mechanical Systems (MEMS), integrated angular velocity microsensor, angular velocity, Coriolis force, mixed-signal simulator SMASH, Verilog-AMS, computer-aided design.**

I. INTRODUCTION

The progress of microelectronics and micromechanics technologies has enabled to create a new qualitative class of devices. Such devices are called Micro-Electro-Mechanical Systems (MEMS). The main feature of MEMS is the combining of electronic control and signal processing circuits (microprocessor module) and mechanical modules or components (microsensors, microactuators, microengines and many others) in a single chip. Among MEMS, a special group of inertial sensors for measuring motion parameters can be distinguished – integrated accelerometers and angular velocity sensors (MEMS gyroscopes). Nowadays, MEMS sensors for measuring motion parameters are widely used in the different engineering areas: automotive industry (suspension and braking systems), military applications (artillery shells, missiles and torpedoes), digital camcorders (image stabilizers) and many others. Integrated angular velocity microsensor is one of the most complex MEMS by both working principle and construction of its mechanical module.

Today's MEMS fabrication, improvement of their technical-exploitable characteristics, decrease of the full cycle for applications of new products depend on both the design automation of the integrated devices and the technological process of their manufacturing. MEMS design process using the advanced technologies requires to optimize technological process, construction of the integrated device and electronics circuits simultaneously, therefore MEMS optimization is an essential part of the modern manufacturing process of the integrated devices. Works related to the development of mathematical and behavioral models in the languages VHDL-AMS, Verilog-AMS for description of such complex heterogeneous systems as MEMS is an actual task for their automated design.

II. WORKING PRINCIPLE AND MATHEMATICAL MODEL OF MECHANICAL MODULE OF INTEGRATED ANGULAR VELOCITY MICROSENSOR

In Fig. 1, 2 model and construction of the mechanical module of the integrated angular velocity microsensor are shown. Mechanical module consists of the sensitive element, spring suspension, inner and outer beams that connect the sensitive element with the spring suspension, and the spring suspension with anchors, which are connected to the substrate of the integrated device respectively. Working principle of the mechanical module of the integrated angular velocity microsensor is the following. The electrostatic force generated by comb drives $F(t)=F_0 sin(\omega t)$ causes the translational vibrations of the inertial sensitive element with the spring suspension with the prescribed amplitude and frequency (drive mode) on *x*-direction. When the platform on which the integrated device is installed, rotates about its sensitivity axis (*y*-axis) with the angular velocity Ω, the Coriolis inertia force appears. The Coriolis force of inertia changes at the frequency of the drive vibrations, and its module is proportional to the measuring angular velocity Ω. As result, Coriolis force causes the translational vibrations of the sensitive element along z-axis, they are called the sense vibrations (sense mode). Amplitudes of these vibratiions are proportional to the angular velocity of the platform rotation, and their phase – to rotation direction.

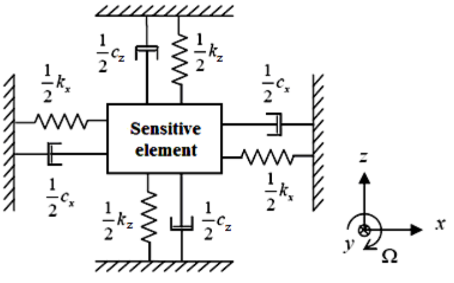

Fig. 1 Schematic view of the model "sensitive element-spring-damper" (where c_x, c_z – damping coefficients, k_x, k_z – spring constants of the spring elements on *x*- and *z*-direction respectively)

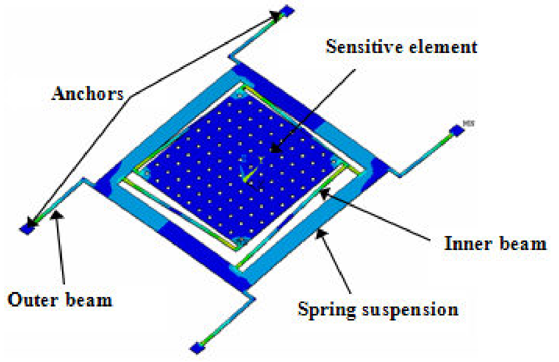

Fig. 2 Construction of the mechanical module of the integrated angular velocity microsensor

Motion of the sensitive element can be described by the following differential equations of the second order [2]:

$$m\frac{d^2x}{dt^2}+c_x\frac{dx}{dt}+k_x x=F_0\sin(\omega t) \quad (1)$$

$$m\frac{d^2z}{dt^2}+c_z\frac{dz}{dt}-2m\Omega\frac{dx}{dt}+k_z z=0 \quad (2)$$

where m – working mass; c_x and c_z – damping coefficients on x- and z – directions, respectively; k_x and k_z – spring constants of the beams on x- and z – directions, respectively.

Spring constants of the beams on x- and z – axes can be obtained from the formulas [4]:

$$k_x=\frac{Ehw^3(4L_b\times L_a)}{L_b^3(L_a+L_b)},$$

$$k_z=\frac{4Ew\left(\frac{h}{L_a}\right)^3}{1+\frac{L_b}{L_a}\left(\left(\frac{L_b}{L_a}\right)^2+12\frac{1+\nu}{1+\left(\frac{w}{h}\right)^2}\right)} \quad (3)$$

where E – Young's modulus; ν – Poisson's ratio; w and h – width and height of the sensitive element structure; L_a, L_b – geometric dimensions of the beams.

Amplitude of the electrostatic force generated by the comb drives, which excites the drive vibrations, can be calculated by the formula [4]:

$$F_0=\frac{\varepsilon_0\varepsilon_r NhV^2}{g_0} \quad (4)$$

where N – number of the comb drive electrodes; h – height of the comb drive electrode; V – supply voltage; g_0 – distance between the comb drive electrodes; ε_r – dielectric permeability of environment between the electrodes; ε_0 – vacuum permittivity ε_0= 8,8541×10^{-12} F/m.

When the sensitive element vibrates at resonance, solving the equations (1) and (2) we obtain:

$$x(t)=-x_m\cos\omega_x t \quad (5)$$

$$Z(t)=\frac{2m\Omega\omega_x x_m}{k_x}\frac{1}{\sqrt{\left(1-(\omega_x/\omega_z)^2\right)^2+(\omega_x/\omega_z)^2}}\times \quad (6)$$

$$\times\sin\omega_x t-\phi$$

where x_m – amplitude of the vibrations at resonance in the direction of x-axis:

$$x_m=\frac{F_pQ_x}{k_x} \quad (7)$$

Quality factors on the x- and z- directions can be obtained from the formulas [4]:

$$Q_x=\frac{m\omega_x}{c_x},\quad Q_z=\frac{m\omega_z}{c_z} \quad (8)$$

Resonant frequencies of the drive and sense vibrations can be obtained from the formulas:

$$\omega_x=\sqrt{\frac{k_x}{m_x}},\quad \omega_z=\sqrt{\frac{k_z}{m_z}} \quad (9)$$

Amplitude of the Coriolis force exciting the sense vibrations we can obtain using the following formula:

$$F_c=2m\Omega\frac{dx}{dt}=\frac{2m\Omega\omega_x Q_x F_p}{k_x} \quad (10)$$

Amplitude magnitude of the sense oscillations is calculated by the formula:

$$z=\frac{Q_zF_c}{k_z} \quad (11)$$

On the sensitive element (rotor), substrate and cover (stators) of the integrated microsensor, electrodes are deposited, which form a differential capacitor (Fig. 3). Capacitances of the differential capacitor C_1 and C_2 are changed when the sensitive element vibrates in the direction of z-axis.

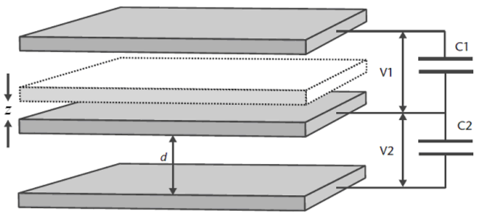

Fig. 3 Differential capacitor formed by the electrodes deposited on the mechanical sensitive element (rotor), substrate and cover (stators) of the integrated microsensor

$C_1 = C_2$ at $\Omega = 0$ and $C_2 - C_1 \neq 0$ at $\Omega \neq 0$

Capacitances of the differential capacitor C_1 and C_2 can be calculated by the formulas:

$$C_1=\varepsilon_0\varepsilon_r S\frac{1}{z_1}=\varepsilon_0\varepsilon_r S\frac{1}{d+z}=C_0-\Delta C,$$

$$C_2 = \varepsilon_0\varepsilon_r S\frac{1}{z_2} = \varepsilon_0\varepsilon_r S\frac{1}{d-z} = C_0 + \Delta C \qquad (12)$$

where S – area of the electrode plate of the capacitor; ε_r – dielectric permeability of environment between capacitor plates; ε_0 – dielectric permeability of vacuum; d – distance between capacitor plates at $\Omega = 0$; z – sense vibrations of the sensitive element.

When $\Omega = 0$, capacitances of the differential capacitor C_1 and C_2 are equal, since $z_1 = z_2$. When $\Omega \neq 0$ respectively $z_1 \neq z_2$, then the difference of the capacitances of the differential capacitor we can calculate using the following formula:

$$C_2 - C_1 = 2\Delta C = 2\varepsilon_0\varepsilon_r S\frac{z}{d^2 - z^2} \qquad (13)$$

Across the capacitor plates the square wave signals are applied at the carrier frequency in the range of a few MHz and with amplitude V_s (Fig. 4). Phase shift of the signals is equal to 180°.

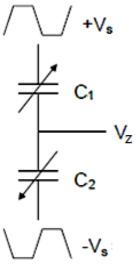

Fig. 4 Electronic circuit for conversion of the capacitance changes into the voltage

Output voltage V_z is directly proportional to the sample frequency V_s and current displacement of the sensitive element z and inversely proportional to the distance between the electrode-plates of the differential capacitor z in the absence of the about the sensitive axis of the microsensor y:

$$(V_z - V_s)C_1 + (V_z + V_s)C_2 = 0,$$

$$V_z = V_s\frac{C_1 - C_2}{C_1 + C_2} = \frac{z}{d}V_s \qquad (14)$$

Currents flowing through the capacitors C_1 and C_2, can be calculated from the formulas:

$$i_1 = \frac{dC_1(z)(V_z - V_s)}{dt}, \qquad i_2 = \frac{dC_2(z)(V_z + V_s)}{dt} \qquad (15)$$

III. Development of Verilog-AMS Behavioral Model of Mechanical Module of Integrated Angular Velocity Microsensor

At the schematic level of MEMS design, behavioral models can be developed. The feature of such models is that they can contain information from the different scientific and engineering areas. As example, in the model of the integrated angular velocity microsensor manufactured by MEMS technologies, magnitudes from mechanics, electrical engineering and electronics are used. In Fig. 4, the behavioral model of the mechanical module of the integrated angular velocity microsensor developed in Verilog-AMS is shown.

```
`include "disciplines.vams"
`include "constants.vams"
module gyro_drive_mode (tmass, tmref, velx); // drive mode
of the sensitive element vibrations
  inout tmass, tmref, velx;
  kinematic tmass, tmref;
  velocity velx;
  acceleration accelx;
  // mechanical properties
  real Mx = 0.16n; // mass
  real Dx = 4u; // damping coefficients on x-axis
  real Kx = 2.6455; // spring constants on x-axis
  real freqx = 3485;
  real Qx = 100;
  real posx;
  analog begin
    // calculation of dynamic characteristics
    posx = Pos(tmass);
    Vel(velx) <+ ddt(Pos(tmass));
    Acc(accelx) <+ ddt(Vel(velx));
    // Kx = Mx*(2*`M_PI*freqx)**2;
    // Dx = Mx*2*`M_PI*freqx/Qx;
    F(tmass, tmref) <+ Kx*posx + Dx*Vel(velx) +
Mx*Acc(accelx);
  end
 endmodule
module gyro_sense_mode (tmass, tmref, tetop, temid, tebot);
  inout tmass, tmref, tetop, temid, tebot;
  kinematic tmass, tmref, pos;
  electrical tetop, temid, tebot;
  velocity velz;
  acceleration accelz;
  electrical vdiff_tm, vdiff_bm, vdiff_dtm, vdiff_dbm;
  ecurrent i1, i2;
  capacitance c1, c2;
  // mechanical properties
  real Mz = 0.16n; ////34n; // mass
  real Dz = 4u; // damping coefficients on z-axis
  real Kz = 2.6455; // spring constants on z-axis
  real freqz = 3484;
  real Qz = 100;
  // geometric dimensions
  real S = 420e-6*420e-6; // area of capacitor plate
  real D = 1.5e-9; // initial distance between capacitor
   …
```

Fig. 5 Verilog-AMS model of the mechanical module of the integrated angular velocity microsensor

IV. Results of Computer Simulation

The simulation results are graphically illustrated in Fig. 6-11 at the applied sinusoidal angular velocity 10 degrees/sec. From the conducted analysis of the obtained simulation results, we can make a conclusion that highly accurate amplifiers and high-sensitive electronic circuits for processing such small changes of the signals are required.

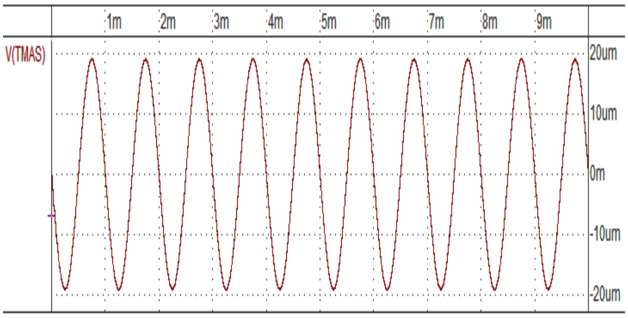

Fig. 6 Drive vibrations of the sensitive element on *x*-direction

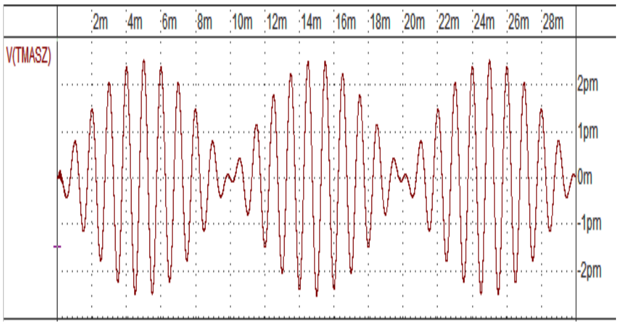

Fig. 7 Sense vibrations of the sensitive element on *z*-direction

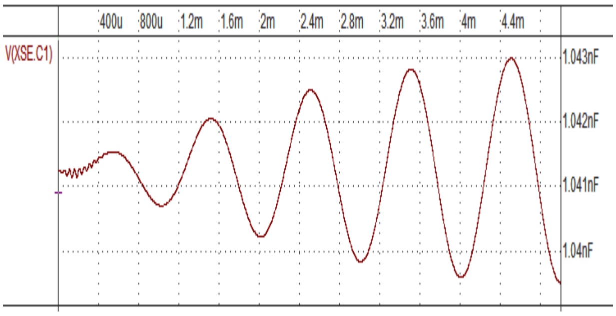

Fig. 8 Capacitance change C_1

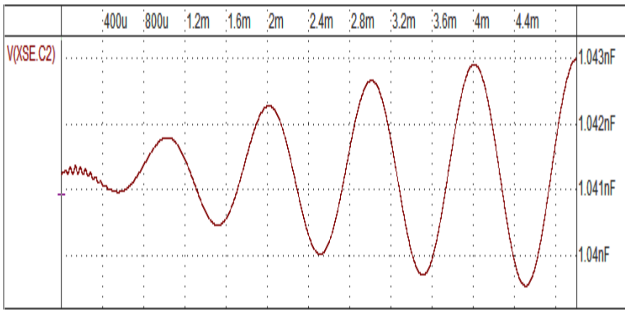

Fig. 9 Capacitance change C_2

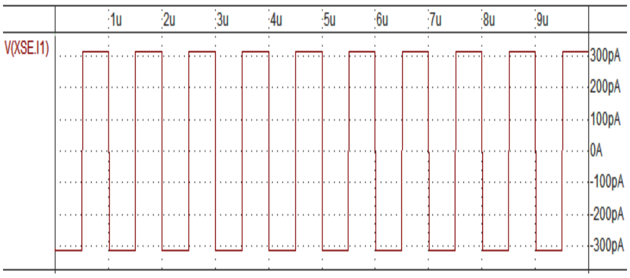

Fig. 10 Change of output current flowing through C_1

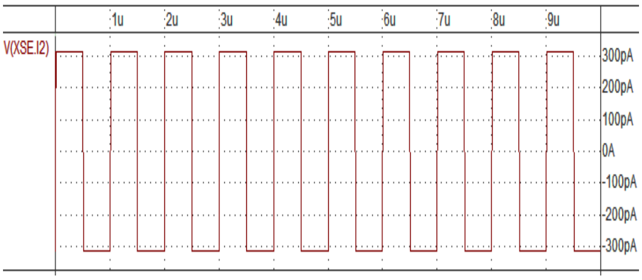

Fig. 11 Change of output current flowing through C_2

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V. CONCLUSIONS

Verilog-AMS model of the mechanical module of the integrated angular velocity microsensor for computer-aided design has been developed. By using the developed model, the drive and sense oscillations of the sensitive element, capacitance changes, changes of output voltages and currents, and sensitivity of the mechanical module of the integrated microsensor depending on the applied angular velocity can be performed and also the behavioral analysis of the mechanical module of the integrated device at the schematic level of MEMS design can be conducted.

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