Verilog – ams model of comb-drive sensing element of integrated capacitive microaccelerometer for behavioral level of computer aid design

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Abstract. The article presents Verilog – AMS model of the comb-drive sensing element of the integrated capacitive microaccelerometer. The suggested model allows to simulate the reaction of the sensing element effected by the applied force of acceleration, changes of its comb-drive capacities, output voltages and currents for determining its constructive parameters and for analysis of the mechanical module of the integrated device at the behavioral level of computer-aided design.

Key words: micro-electro-mechanical systems (MEMS), micromachining technologies, micromechanical comb-drive sensing element, integrated capacitive microaccelerometer, acceleration, SMASH, Verilog – AMS hardware description language, computer-aided design.

INTRODUCTION

We face now a remarkable progress in developing new technologies accompanied by their more advanced parameters comparing with the present day practice. One of them is the technology of micro electromechanical systems (MEMS) [1-3] These systems allow to manufacture the devices which proved to be cheaper, lighter and more delicate then their analogues in the macro world. In addition, such devices are more reliable as they are manufactured with the use of integrated technologies. They are also given the perspective of growing their functionality and quite a number of other advantages [4-7].

MEMS technologies are used in various fields of science and engineering as well as in developing different mechanisms [3, 8, 9] for improving their output parameters. Such technologies are used in realization of sensors of different functional purposes, actuators, medical micro instruments. MEMS technologies are in particularly wide use when realizing inertial sensors. Such MEMS inertial sensors as accelerometers [10] and gyroscopes [11] are widely used in many fields of engineering: automobiles (systems of controlling safety backs, antiblocking ABS systems, antislipping systems, systems of active suspension, etc.), medical service and consumer electronics (smartphones, hand-held computers, notebooks, video-playing consoles, systems of stabilization in photo and video cameras, systems of monitoring engineering structures (machines and bridges), inertial and navigation systems, determining concentration of harmful gases, etc. [1-3, 5, 6, 12-16].

To make an effective design of such sensors, to provide them with the necessary technical and operating characteristics, to improve their reliability, the behavioral models are made up in the hardware – description language (VHDL-AMS, Verilog-AMS) with the use of the following software: Cadence, MATLAB, hAMSter, SMASH (Dolphin integration) and others [17] therefore, operations connected with developing behavioral models and automation of their design in the languages VHDL-AMS, Verilog-AMS aimed at description of such compound heterogeneous systems as MEMS are of a particular importance now. There exists quite a number of various constructions of accelerometers [3, 18-20] but in case with microaccelerometers the most common type of constructions is the comb one. The mentioned above constructions have VHDL-AMS models [21-24] However, most of them do not consider in a satisfactory way constructively – technological parameters which have a sufficient effect on the initial parameters of a microaccelerometer.

MAIN PRESENTATION

We suggest a typical structure (Fig 1) of the comb-constructioned sensing element of the integrated capaci tive microaccelerometer [25]. The sensing element comprises the operational mass suspended on the elastical elements fixed to the pad of an integrated device; movable comb electrodes suspended to the operational mass and immovable comb electrodes suspended to the pad of an integrated device. Movable and immovable comb electrodes make up a comb drive. At the moment of external acceleration starting, the operating mass accompanied by movable comb electrons begins to move under the impact of the force of inertia with the simultaneous alteration of the distance between the movable and immovable electrodes of the comb drive. As comb drive electrodes compose differential capacit couple of C_1 and C_2, any changes made within the mentioned above capacity will provoke changing of these capacity.

We shall start our analysis of the integrated capacitive microaccelerometer from the equation describing its sensing element movement:

$$M\frac{d^2x(t)}{dt^2}+D_y\frac{dx(t)}{dt}+K_x x(t)=-F_{ext}\ , \quad (1)$$

where: M – mass of the sensing element, D_y – coefficient of attenuation, K_y – coefficient of elasticity, $x(t)$ – movement of the sensing element across the axis x. $F_{ext} = M\cdot a_{ext}$, where $aext$ – external acceleration.

Mass M of the sensing element may be calculated by means of the formula:

$$M=\rho\left(V_{mass}+V_{fingers}\right)=\rho\left(W_{pm}L_{pm}+(N_s+N_f)L_{sf}W_{sf}\right)T\ , \quad (2)$$

where: ρ – specific density of the material (for polysilicon ρ = 2330 kg/m³), V_{mass} and $V_{fingers}$ – volumes of the operating mass and movable comb electrodes correspondingly.

System of suspension of mechanically sensing elements comprises four curved elastic paralelly connected elements (Fig 1). Coefficient of inelasticity connected elements (Fig 1). Coefficient of inelasticity of one section of elastic elements is calculated by means of formula [26, 27]:

$$K_{beam}=\frac{12\,EI_s}{L_s^3}\ , \quad (3)$$

where: E = 170×10 H/m² – poly-silicon module of Ewing; L_s – inertial moment of the elastic element which is calculated on the basis of the formula $\frac{W_sT^3}{12}$; W_s, L_s, and T – width, length and thickness of one section of the elastic element correspondingly.

As two sections of the curved elastic elements possess similar lengthes and are connected successionally, the elasticity coefficient of one curved elastic element is determined by the formula:

$$K_{fold}=\frac{1}{2}K_{beam}=\frac{EW_sT^3}{2L_s^3}\ . \quad (4)$$

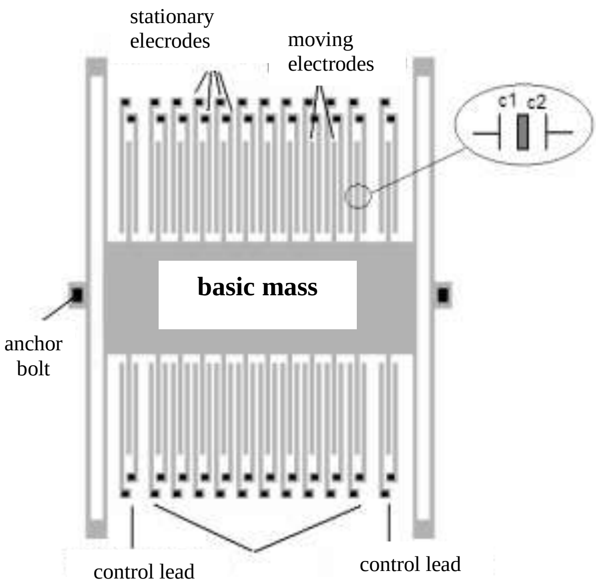

Fig. 1. Schematic representation of the comb structure of MEMS capacitive micro accelerometer sensing element

As the operational mass is suspended on four elastic elements of the single length, each elastic element receives 1/4 of the total force of loading. Therefore, the total coefficient of elasticity equals $4\times K_{fold}$:

$$K_{mechanical}=4\times K_{fold}=\frac{2EW_sT^3}{L_s^3}\ . \quad (5)$$

The suggested above formula for calculating coefficients of inelasticity does not take into consideration the effect of electrostatic moderation of elasticity. After application of simulating voltage of high frequency $V_m(t)$ to immovable comb electrodes, electrostatic forces are generated in metering drive. These forces cause modifications in mechanical inelasticity of elastic elements of suspension. This phenomenon is called moderation and is observed in the model of mechanical sensing element. The resulting force effecting the comb electrode (F_s) may be calculated by means of the following formula:

$$F_e=F_{e1}-F_{e2}=\frac{\varepsilon_0 AV_m^2}{2}\left[\frac{1}{(d_0-x)^2}-\frac{1}{(d_0+x)^2}\right], \quad (6)$$

where: F_{e1} and F_{e2} – electrostatic forces; d_0 – initial distance between movable and immovable electrodes of the comb drive; x – replacement of the movable electrode; A – side area of metering comb electrode ($A=L_{sf}T$); Ɛ ε_0 – dielectric constant ($8{,}85\times10^{-12}$ F/m) and V_m – amplitude of voltage of modulation.

Suppose, $x \ll d_0$ and N_s – number of comb electrodes. Then electrostatic coefficient of elasticity may be calculated by means of the formula:

$$K_e=N_s\left(\frac{d(F_e)}{dx}\right)=-N_s\left(\frac{2\varepsilon_0 L_{sf}TV_m^2}{d_0^3}\right). \quad (7)$$

Accordingly, effective coefficient of elasticity equals:

$$K=K_{mechanical}+K_e\ . \quad (8)$$

During replacement of movable structure air flow crosses the clearance between movable and immovable structures. For capacitive mechanical sensing element dumping of the condensed layer of air between comb electrodes is dominative over all the rest forms of dumping. Effect of dumping between comb electrodes may be simulated by the low of Hagen – Poiseuille [28]. Thus, we get the following formula for calculating coefficient of attenuations:

$$D = 14,4(N_f + N_s)\mu L_{sf}\left(\frac{T}{d_0}\right)^3, \quad (9)$$

where: N_s and N_f – number of metering and controlling comb electrodes, correspondingly; L_{sf} and T – length and thickness of movable comb electrodes; d_0 – initial distance between immovable and movable comb electrodes; and μ – coefficient of aid viscosity ($1,1839\times10^{-5}$ Pa·s).

The received parameters may help in determining operational parameters. The resonant frequency (f_0) may be calculated considering mass (M) and the effective coefficient of elasticity (K):

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{K}{M}}. \quad (10)$$

Coefficient of quality (Q) of mechanical sensing element may be received considering the following parameters: operational mass (M), coefficient of elasticity (K) and coefficient of attenuation (D):

$$Q = \frac{\sqrt{KM}}{D} = \frac{M\omega_0}{D}. \quad (11)$$

Dynamic response of mechanically sensing element may fall into three types according to the value of the coefficient of quality Q: if $Q < 0,5$, the sensing element is sufficiently dumping; if $Q = 0,5$ the sensing element is critically dumping. In other case we get weakly dumping.

Electrodes of comb drive make up differential condenser (Fig 2). When the external acceleration is absent, static capacity of such differential condenser may be calculated by means of the formula:

$$C_1 = C_2 = C_0 = \frac{\varepsilon_0\varepsilon_r N_s L_{sf} T}{d_0}. \quad (12)$$

When external acceleration appears, the operational mass begins to move under the impact of inertial force in the direction of axis x and causes changes of C_1 and C_2 of differential condenser which may be calculated by formula:

$$C_1 = \frac{\varepsilon_0\varepsilon_r N_s L_{sf} T}{d_0 + x} = \frac{\varepsilon_0\varepsilon_r N_s L_{sf} T}{d_0(1 + x/d_0)} \approx \frac{\varepsilon_0\varepsilon_r N_s L_{sf} T}{d_0}\cdot\left(1 - \frac{x}{d_0}\right). \quad (13)$$

$$C_2 = \frac{\varepsilon_0\varepsilon_r N_s L_{sf} T}{d_0 - x} = \frac{\varepsilon_0\varepsilon_r N_s L_{sf} T}{d_0(1 - x/d_0)} \approx \frac{\varepsilon_0\varepsilon_r N_s L_{sf} T}{d_0}\cdot\left(1 + \frac{x}{d_0}\right), \quad (14)$$

where: ε_0 – dielectric constant; ε_r – relative dielectric environmental penetrability between the plates of condenser; d_0 – distance between the plates of condenser at $a_{ext} = 0$; x – replacement of the sensing element.

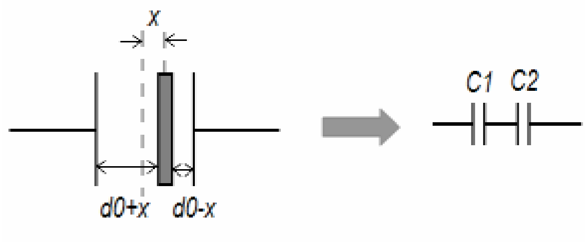

Fig. 2. Differential capacitor formed by the interdigitated electrodes with capacitors C_1 and C_2.

The initial signal is proportional to the oscillations of the carrier frequency and the changes of capacitors of differential condenser, and, thus, to external acceleration a_{ext}. As:

$$C_2 - C_1 = \frac{2\varepsilon_0\varepsilon_r N_s L_{sf} T}{d_0}\cdot\left(\frac{x}{d_0}\right) = 2C_0\cdot\left(\frac{x}{d_0}\right), \quad (15)$$

$$C_1 + C_2 = \frac{2\varepsilon_0\varepsilon_r N_s L_{sf} T}{d_0} = 2C_0. \quad (16)$$

The value of initial signal V_{out} is directly proportional to the carrier frequency and movement of the sensing element. It is inverse proportional to the initial distance between the movable and immovable electrodes of the comb drive (distances between covers of differential capacitors couple at $a_{ext} = 0$):

$$V_{out} = \frac{C_2 - C_1}{C_1 + C_2}\cdot V_{sample} = V_{sample}\left(\frac{x}{d_0}\right). \quad (17)$$

When designing MEMS at the schemotechnical level the construction of behavioral models are foreseen. The specific feature of such models is their ability to contain data of various fields of science and engineering. For example, models of integrated capacitive microaccelerometer contains the quantities of mechanics, electricity and electronics. The language describing facilities of Verilog-AMS (Verilog Hardware Description Language Analog-Mixed Signals) allows to develop digital, analogue and mixed behavioral models which use both electrical and mechanical signals [28, 29]. Parameters of Verilog-AMS behavioral model of the sensing element of comb construction of integrated capacitive microaccelerometer are presented in the tab. 1

Table 1. Parameters of comb structuews of integrated capacitive microaccelerometer sensing element used in Verilog-AMS model

Symbols	Constructional parameter of a sensing element	Value
W_{pm}	Width of operational mass	120 Mkm
L_{pm}	Length of operational mass	450 Mkm
T	Thickness of elastic elements, comb electrodes and operational mass	20 Mkm
L_s	Length of elastic element	176 Mkm
W_s	Width of elastic element	20 Mkm
$W_{sanchor}$	Width of anchor of an elastic element	10,0 Mkm
L_{sf}	Length of comb electrode	150 Mkm
W_{sf}	Initial distance between movable and immovable electrodes of a comb drive	1,5 Mkm
G	Number of metrical comb electrodes	54
N_s	Number of controlling electrodes	4
N_f	Width of the anchor of comb electrode	5,0 <k,

The developed behavioral models made possible simulation using SNASH software [17]. The results are graphically presented in Fig 3. at the synosoidal change of external acceleration of 5g. The received results prove that the initial voltage takes place in the antiphase with the frequency 1MHz and the amplitude of 200pV-1nV. Thus, having such constructive parameters of sensing elements of the microaccelerometer we need precision amplifiers and highly sensing schemes for processing such signals.

CONCLUSIONS

We developed Verilog-AMS model of the sensing comb construction of integrated capacitive microaccelerometer which allows to simulate reaction of the sensing element to the applied force of inertia, i.e. change of capacitors of its comb drive, initial voltage and currents for the given initial quantities of its constructional parameters. This system also gives the opportunity to analyze mechanical components of integral device at the behavioral level of automated design.

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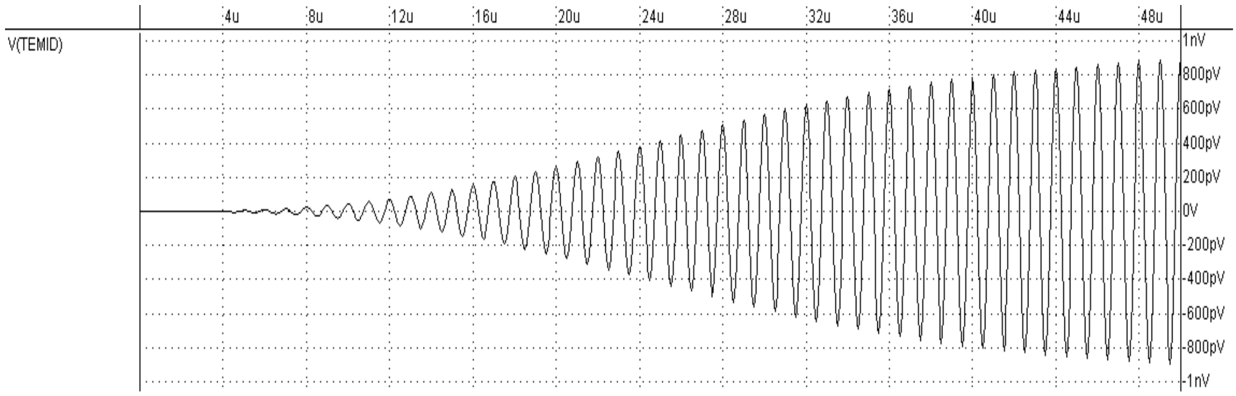

Fig.3. Changing of output voltage V_{out}

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