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Behavioral Modeling and Simulation of an Open-loop MEMS Capacitive Accelerometer with the MATLAB/SIMULINK

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***Abstract* — In this paper, an open-loop MEMS capacitive accelerometer has been modeled and simulated. The capacitive transducer is the simplest configuration which can converts mechanical displacement due to inertial forces to electrical signals. The mathematical modeling contains two distinct phases: modeling of the mechanical elements which include the proof mass and elastic element, and modeling of the readout circuits. The readout circuits contain a charge-mode amplifier and a phase-sensitive demodulator to process the signal obtained from transducer. The accelerometer has a 0.708pF/g resolution and 1 percent nonlinearity for ±5g input acceleration. A MATLAB/SIMULINK based model used to validate the response behavior of the mathematical model.**

***Keyword* - Accelerometer, charge-mode Amplifier, MEMS, phase-sensitive demodulator.**

1. Introduction

It exist much more types of acceleration sensors, but all of these are based on displacement of a proof mass due to inertial forces. There are two basic methods for detecting input acceleration: piezoelectric method and capacitive method [1], [2]. The determination of the input acceleration using piezoelectric method is made using a piezoresistor fixed on the base of the embedded lamella; the piezoresistance is modified by the lamella deviation. One of the great disadvantages of this method is nonlinearity behavior in higher temperatures. The second method (the capacitive method) is developed much enough in the last years due to the possibilities of signal processing with the technology of integrated circuits and miniaturization.

The main goal of this paper is to model and simulate an open-loop MEMS capacitive accelerometer using the MATLAB/SIMULINK model.

2. Basic Operations

An accelerometer is a sensor that measures the physical acceleration by an object due to inertial forces or due to mechanical excitation. In principle the accelerometer operation relies on the action of the input acceleration of a proof mass that has a parallelipipedic shape and is placed on a substrate using for silicon flexible bars (to remove unpredictable modes) [3],[4]. On the same substrate there are two electrodes, placed on opposed sides of the mobile plaque (figure 1).

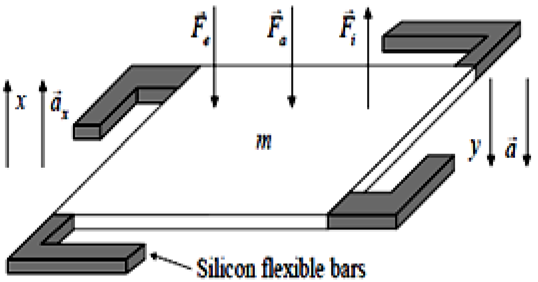

Fig.1. Mechanical model of the accelerometer [5]

The physical quantities from Fig. 1 are: m –proof mass, $\vec{a}$, y acceleration and position of the carrying vehicle, $\vec{a}_x$, x acceleration and proof mass position with respect to the carrying vehicle, $\vec{F}_e$, $\vec{F}_a$, $\vec{F}_i$ - the elastic, the damping and respectively the inertial forces.

$$m\frac{d^2y}{dt^2} = m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx \quad (1)$$

Where k is the resulting elasticity constant, b is the viscous damping coefficient and m is the mass of proof mass.

If the fixed electrodes are supplied by the voltages:

$$v_2 = -v_1 = V_1 \sin \omega t \quad (2)$$

Then the following electrostatic forces will act over the mobile plaque:

$$F_{el1} = \frac{\varepsilon_0 A}{2}\frac{v_1^2}{(d_0 - x)^2} = \frac{\varepsilon_0 A}{4}\frac{V_1^2}{(d_0 - x)^2}(1 - \cos 2\omega t) \quad (3)$$

$$F_{el2} = \frac{\varepsilon_0 A}{2}\frac{v_1^2}{(d_0+x)^2} = \frac{\varepsilon_0 A}{4}\frac{V_1^2}{(d_0+x)^2}(1-\cos 2\omega t) \qquad (4)$$

Where A is the proof mass area, $\varepsilon_0 = 8.85\times10^{-12} F/m$, and d_0 is the initial gap.

The frequency of supplying voltage is very high ($f = 100KHz$), so the electrostatic forces can be assumed as constant and we have:

$$F_{el} = F_{el1} - F_{el2} = \frac{\varepsilon_0 A V_1^2}{d_0^3}x \qquad (5)$$

Hence, the mechanical transfer function is:

$$H(S) = \frac{X(s)}{a(s)} = \frac{1}{s^2 + \frac{b}{m}s + \left(\frac{k}{m} - \frac{Fel}{m}\right)} \qquad (6)$$

3. Modeling and Simulation of the Accelerometer Blocks

3.1. Mechanical Part

When $\vec{a}_x \neq 0$, the variable capacitors will be change asymmetrically.

$$\begin{cases} C_0 = \dfrac{\varepsilon_0\varepsilon_r A}{d_0} \\ C_1 = \dfrac{\varepsilon_0\varepsilon_r A}{d_0 - x} \;\&\; \begin{cases} C_1 = C_0 + \Delta C \\ C_2 = C_0 - \Delta C \end{cases} \rightarrow \Delta C = \dfrac{C_0 d_0 A}{d_0^2 - x^2} \\ C_2 = \dfrac{\varepsilon_0\varepsilon_r A}{d_0 + x} \end{cases} \qquad (7)$$

In equation (7), C_0 is the nominal capacitor (when $\vec{a}_x = 0$), C_1 and C_2 are the variable capacitors.

In order to simulate the system, we have the following parameters ([7]):

$m = 4.313\mu g, k = 149.94N/m,$

$b = 0.05545Ns/m^2, d_0 = 10\mu m,$

$A = 12mm^2, C_0 = 10.62pF,$

$V_1 = 0.5V, f = 100kHz.$

Fig. 1 depicts the SIMULINK based model for mechanical elements.

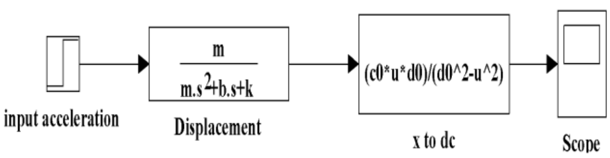

Fig.2. SIMULINK model of mechanical part

The curves from Fig. 7 and Fig. 8 present the steady values of $x(a)$ and $\Delta C(a)$ for acceleration within the range $\pm10g$.

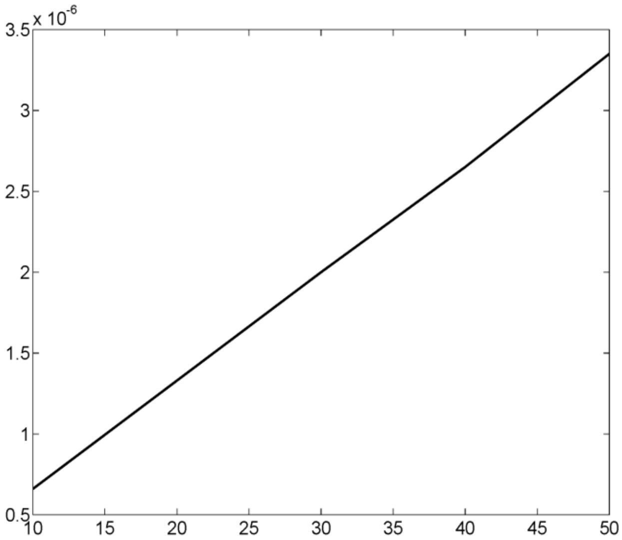

Fig.3. The steady values of

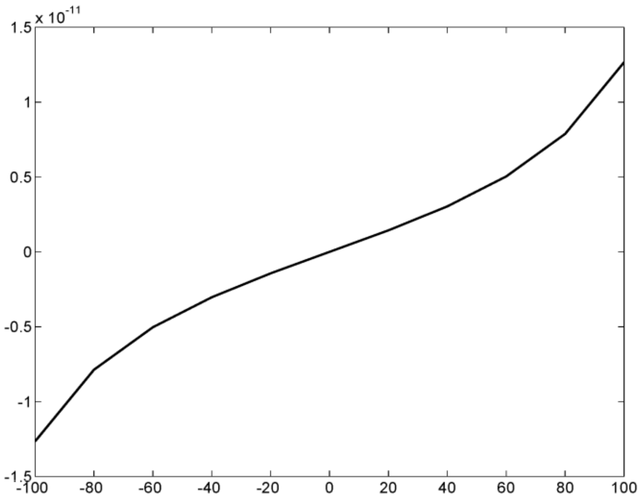

Fig.4. The steady values of $\Delta C(a)$

From Fig. 3 the dependency of $x(a)$ is approximately linear and the curve of $\Delta C(a)$ reveals the introducing of some strong non-linearities for higher accelerations of $\pm4g$.

4. Charge-Mode Amplifier and Phase-Sensitive Demodulator

Fig. 5 illustrates a transimpedance amplifier (TIA) in order to convert capacitance signal to electrical signal [8].

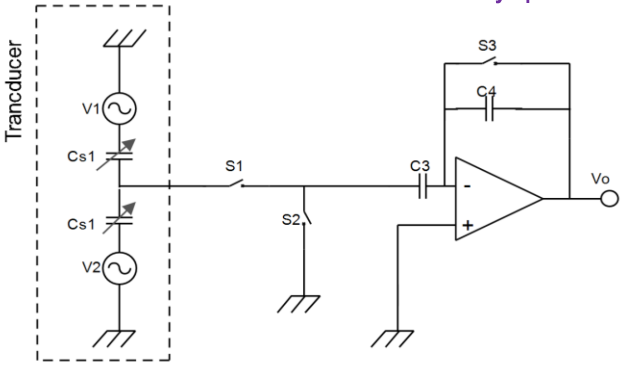

Fig.5. Charge-mode amplifier [8]

In order to determine the positive or negative acceleration, we have to use a phase sensitive demodulator as shown in Fig. 6 [9].

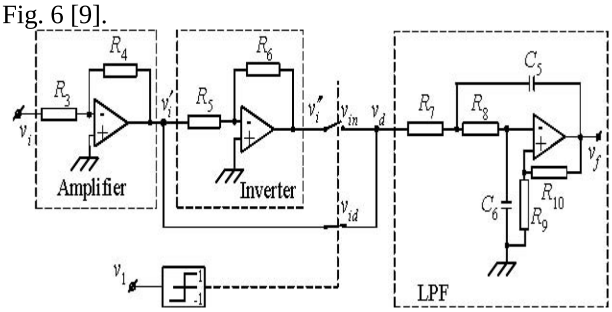

Fig.6. Phase sensitive demodulator [9]

The low pass filter transfer function is:

$$\frac{v_f(S)}{v_d(S)} = \frac{KA}{a_2 s^2 + a_1 s + 1} \ \& \ \begin{cases} KA = 1 + \dfrac{R_{10}}{R_9} \\ a_2 = R_7 R_8 R_9 C_5 C_6 \\ a_1 = C_6\left(R_7 + R_8\right) - \dfrac{C_5 R_7 R_{10}}{R_9} \end{cases} \quad (8)$$

In order to simulate the model, the following values of parameters were used [10].

$R_{4,5,6} = 10K\Omega, R_3 = 1K\Omega,$

$K_A = 3.12, a_1 = 0.3888\times10^{-3},$

$a_2 = 72.9\times10^{-9}, C_3 = 1nF,$

$C_4 = 22nF.$

The output of the phase sensitive demodulator can be calculated with [11], [12]:

$$v_f = KAv_d(t) = \frac{K_A}{T}\left[\int_0^{T/2}\left(-K_a v_i(t)\right) + \int_{T/2}^{T}\left(K_a v_i(t)\right)dt\right] = \frac{2K_aK_A}{\pi}\cdot\frac{2\varepsilon AV_1}{C_4}\cdot\frac{x}{d_0^2 - x^2} \quad (9)$$

Where T represent the period of signal $v_i(t)$ that generates $v_d(t)$. Since $x << d_0$, we have:

$$v_f \cong \frac{2K_aK_A}{\pi}\cdot\frac{2\varepsilon AV_1}{C_4}\cdot\frac{x}{d_0^2} \quad (10)$$

Consequently the output signal v_f is approximately linear with the displacement x of the proof mass and consequently with the input acceleration. It should be notice that the input acceleration should not exceed $\pm 4g$.

5. Simulation of the Entire Open-Loop Capacitive Accelerometer

The SIMULINK based model that was used for the phase sensitive demodulator and entire simulation of the MEMS capacitive accelerometer is depicted by Fig. 9 and Fig. 10 respectively.

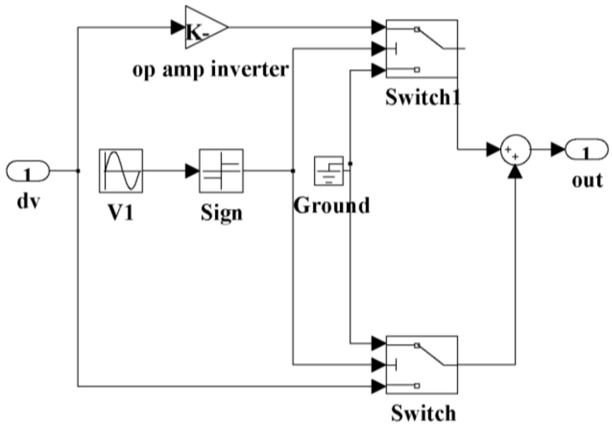

Fig.7. The SIMULINK based model of the phase sensitive demodulator

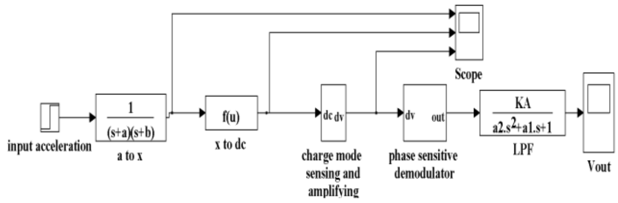

Fig.8. SIMULINK based model of the entire accelerometer

In order to simulate the accelerometer for positive and negative acceleration, the value of step-like acceleration signal is $a = 1g$.

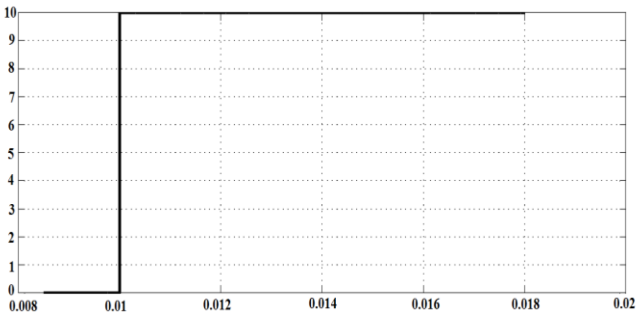

Fig.9. Positive input acceleration

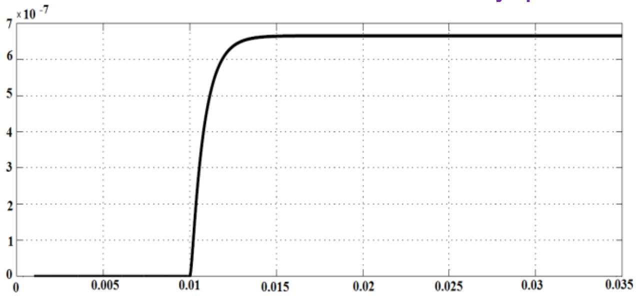

Fig.10. Displacement

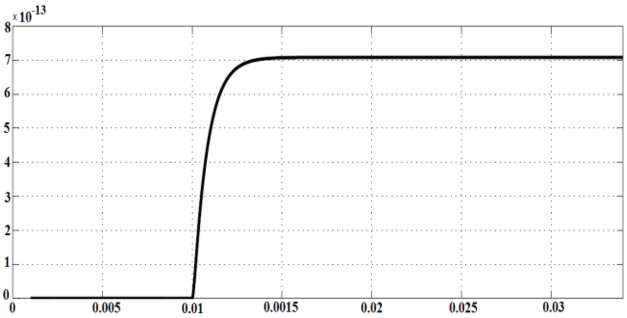

Fig.11. Differential capacitance

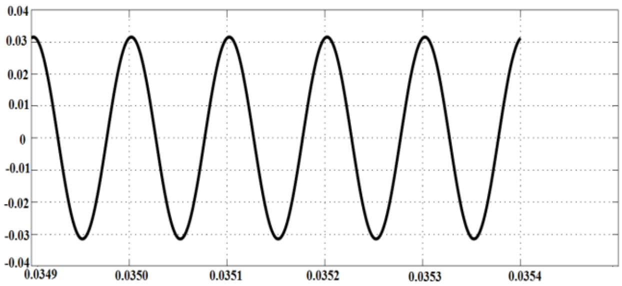

Fig.12. The output of the charge-mode amplifier

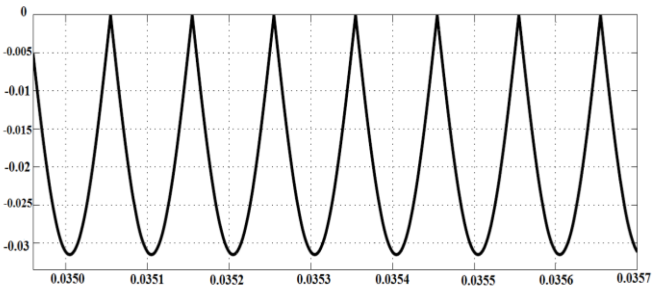

Fig.13. The output of the phase sensitive demodulator

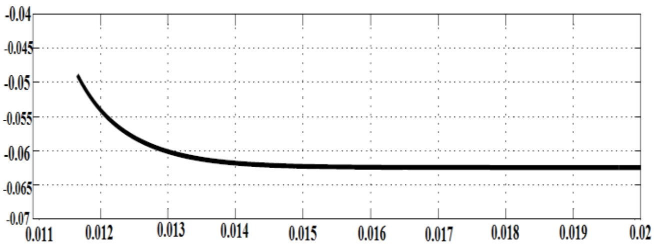

Fig.14. The output voltage signal for $a = 1g$

6. Conclusion

In this paper, an open-loop MEMS capacitive accelerometer was presented. In order to decrease steady state error, a force feedback in close-loop configuration and a PID controller should be used.

The simulated accelerometer is suitable for $a = \pm 4g$. The simulation result is shown in table 1.

Accelerometer sensitivity	0.708pF/g
Proof mass displacement	0.66μm
Differential capacitance	0.708pF
The magnitude of the output signal	0.03V

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