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Siddharth Thakurdesai
Dept. of Electronics and Telecom., Priyadarshini COE, Nagpur, Maharashtra, India.

Bithika Jha
Dept. of Electronics and Telecom. Priyadarshini COE, Nagpur, Maharashtra, India.

Parmita Borkar
Dept. of Electronics and Telecom Priyadarshini COE, Nagpur, Maharashtra, India.

Correspondence
Siddharth Thakurdesai
Dept. of Electronics and Telecom., Priyadarshini COE, Nagpur, Maharashtra, India.

Mathematical modeling of MEMS capacitive accelerometer using sigma-delta analog to digital converter in VHDL-AMS

Siddharth Thakurdesai, Bithika Jha, Parmita Borkar

Abstract
In this paper, we are going to implement an accelerometer using capacitive sensing element [3]. An accelerometer is a device that can detect movement of an object through space. We are using VHDL-AMS as a base for this modeling. VHDL-AMS is a strict subset of the VHDL which is used to model digital hardware and then implement them on an ASIC of FPGA [8]. The AMS extension enables us to model more complicated circuits which use analog components in them. The capacitive sensing element is used over inductive sensor due to its low power requirement and more accurate output yield

Keywords: MEMS, Accelerometer, VHDL-AMS, Capacitive Sensing Element

1. Introduction

The Micro-Electro-Mechanical Systems is an intricate branch of fabrication technology which is used for microscopic circuit design. This design is very complex and minute. Precision driven machines are used to design and implement these circuits. The circuits are designed using mechanical and electrical components such as resistors, capacitors, mass, spring, dash-pot etc. The circuits which are designed using MEMS are so small that they cannot be seen with naked eyes.
Accelerometer is modeled in two parts.

i) Capacitive sensing element
ii) Sigma-Delta Analog to digital Converter [5-6]

The input to the accelerometer will be in form of distortions or vibrations to the main frame on which the accelerometer is mounted. This input signal will be fed to the capacitive sensing element. The output of this block will be in the form of change in capacitance with respect to the displacement or movement of the object itself.

2. Structure of the sensing element: The sensing element of the accelerometer is a transducer which converts the physical acceleration that the object goes through into electrical impulses which can be digitally processed for use in different sensing and feedback systems. The sensing element is based on a MEMS concept. It includes various mechanical and electronic components used together for more efficient results than the mechanical or electrical components used alone. The conceptual model of the sensing element is given below. The description of this model is also covered in detail.
The seismic mass is freely suspended with the help of springs. Capacitive plates are joined to this mass. Also, there are fixed plates across which capacitance is drawn. The springs act as a damping force and also help the mass to achieve its initial position, the one before the acceleration was applied.

3. Operation: When acceleration is applied to the object, accelerometer which is mounted on the surface of the object also undergoes acceleration. The mass is freely suspended inside the sensing element of the accelerometer. This seismic mass moves as a result of the external stimuli that the acceleration is.

This external force of acceleration impacts the mass, springs and the frame. The capacitive plates that are attached to the mass also move with it. The capacitance is generated between the fixed plates and the movable plates and the dielectric between them is the air. As, the movable plates are displaced by the virtue of acceleration applied to the object, the capacitance changes proportionally to the instantaneous value of acceleration at that point.

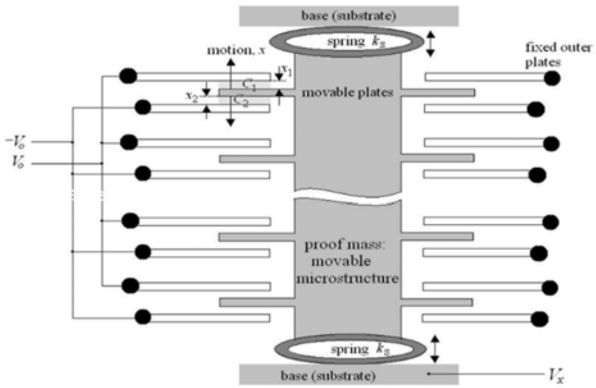

Fig 1: Structure of the capacitive sensing element with seismic mass, capacitive plates and springs [9].

4. Mathematical Model: The mathematical model was designed based on the behavior of the sensing element [3]. Equations were derived which properly described the sensing element in

$$M\frac{d^2x(t)}{dt^2} + Dx\frac{dx(t)}{dt} + Kx\,x(t) = F_{ex}$$

Where, Fex = Externally applied force

M = Seismic mass

Dx = Damping Co-efficient

Kx = Spring Co-efficient

x(t) = Displacement of mass

F_{ex}=M*a_{ex} Where, a_{ex} = external acceleration

$$\Delta c = |c1 - c2|$$

$$c1 = \frac{\varepsilon_0 A}{(d - x)}$$

$$c2 = \frac{\varepsilon_0 A}{(d + x)}$$

where,

c1= capacitance when distance between the parallel plates is reduced.

c2=capacitance when distance between parallel plates is increased.

d=distance between the plates when acceleration is not applied.

x=displacement due to acceleration.

Δc=change in capacitance.

5. VHDL-AMS Model: VHDL is a hardware description language used to define the behavior and structure of any device as long as the circuit can be realized in hardware. The Analog and Mixed Signal Modeling (AMS) subset of VHDL was introduced in 1999 with a view of enabling the designers to model analog and mixed signal systems which can have analog components and devices such as transistors, resistors, capacitors and inductors. The behavior and working of such high level circuits can be easily verified with VHDL-AMS using simulations and then after the behavior is verified, this circuit can then be implemented on hardware [7, 8, 10].

Traditionally, the choice of languages for simulations was orthodox. Spice was used for analog and mixed signal systems. But, now-a-days, VHDL-AMS is being used due to its advanced features and familiarity with the VHDL platform. It is observed that compared to the SPICE model which requires extra voltage and current sources in order to model each phenomenon that can influence the functioning of the semi-conductive device, by using a VHDL-AMS model it is easy to obtain complex models only on basis of its state equations. Taking this into consideration, VHDL-AMS was chosen as a language to implement this device.

The equations derived in the last segment, were modeled in VHDL-AMS using a simulator. Various choices for simulation are available, such as Hamster, Simplorer, Virtuoso etc. and one can use either of them. The output of the first block, the sensing element was given to the sigma-delta modulator which was used to digitize it. The parts of the application reference of the sensing element is given below.

```
library ieee;
library disciplines;
use disciplines.kinematic_system.all;
use disciplines.electromagnetic_system.all;
use disciplines.physical_constants.all;
use IEEE.MATH_REAL.all;
entity sensing_element is
generic ( Delta_C: real;
x: displacement:= 3.0 * 10.0e-6); -- Displacement Final);
port (Area: real:= 16.0 * 10.0e-6; -- Area of plates of capacitor
D0: Displacement:= 200.0 * 10.0e-6; -- Displacement initial
Epsilon: real:= 8.854 * 10.0e-12); -- Epsilon constant
end entity sensing_element;
```

6. Sigma-Delta Modulator: The Sigma-Delta modulator [5, 6] is essentially an analog to digital converter which uses the technique of sampling to convert the analog input applied to its terminals into a discrete digital signal. Basically a sigma delta modulator is a 1-bit sampling system. It uses the concept of oversampling. The analog signal is sampled at a relatively high sampling rate as compared to the signal at the output and then accumulated and averaged using the decimation filter at the output of the sampling circuit. In this way, we get a digitized signal from a completely analog signal of any frequency. For an analog sinusoidal input signal, when the input is above the threshold, the bitstream is equal to logic ‘High’ and when the input is below the threshold, the bitstream is equal to logic ‘Low’. So, when the input signal is close to the positive reference voltage (+V_Ref), more number of ones are generated, whereas when the input signal is close to the negative reference voltage (-V_Ref), more number of zeros occur in the signal waveform.

7. Simulation Results: For the purpose of simulation, hAMSter simulator was used. The results obtained by applying a sinusoidal input of amplitude of 1g for 5 cycles with respect to the clock. The results obtained are given below in figure 3 and 4. The sigma delta modulator converts the analog acceleration applied to it into digital stream of pulses by the principle of operation explained above.

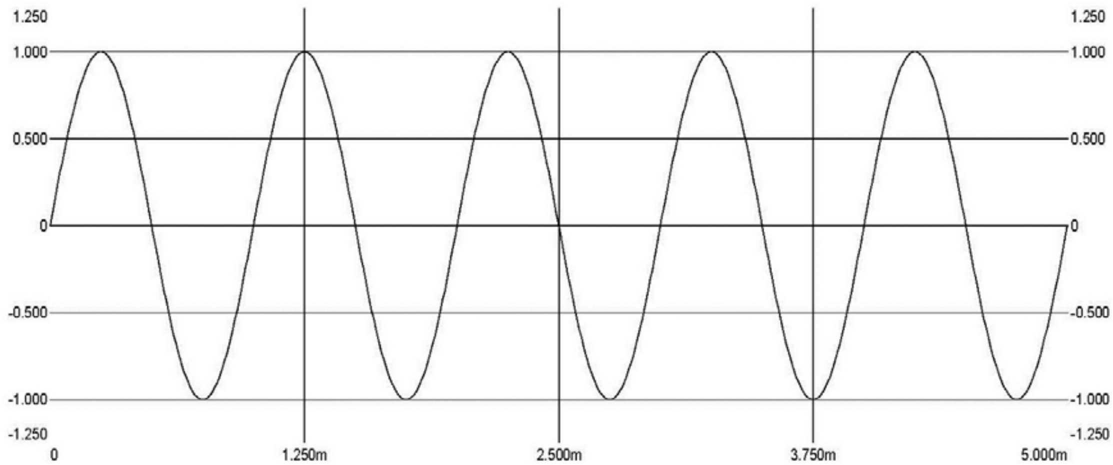

Fig 2: Sinusoidal Signal as an input, applied as the change in acceleration

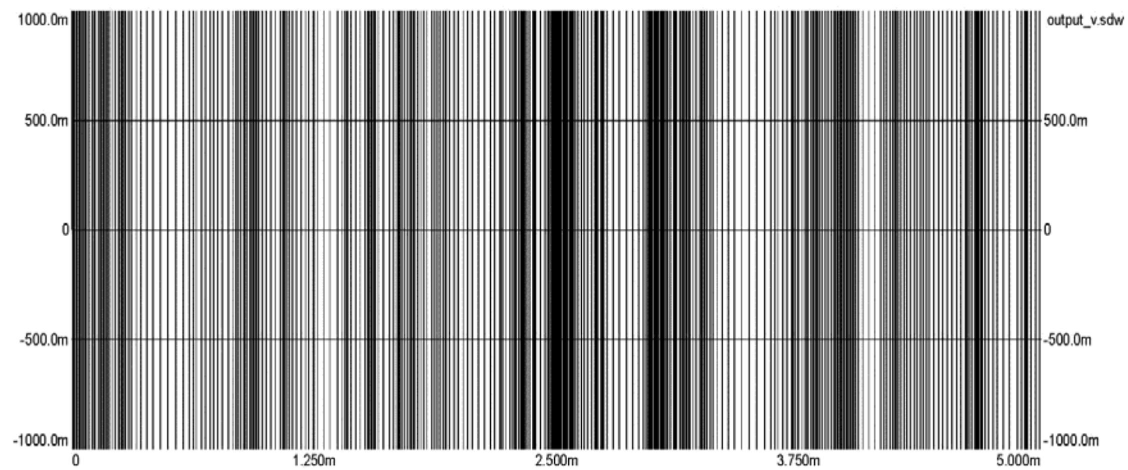

Fig 3: Digital Signal of the Sigma-Delta Analog to Digital Converter

As the results of the simulation are not clearly visible in the figure 3 given above, we have included another under-sampled version in figure 4, by increasing the minimum step size of the same for a clearer picture for a proper perspective of the process.

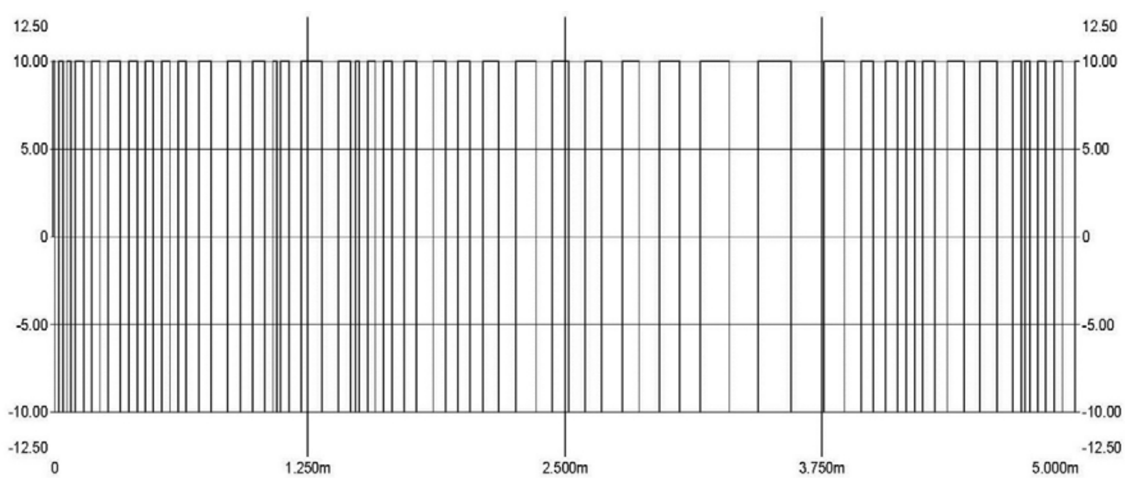

Fig 4: under-sampled version of the original output waveform for a better visibility of the process.

Also, the waveforms of the digitized values of capacitances using the capacitive sensing element are given below in figure 5. As seen from the observations, the values of the capacitors obtained are analogous with the results expected from the mathematical model of the MEMS capacitive accelerometer that we have modeled.

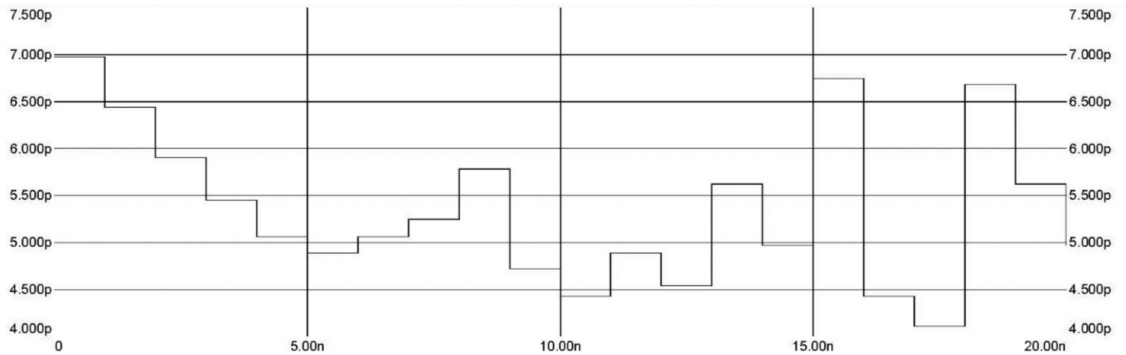

Fig 5 A

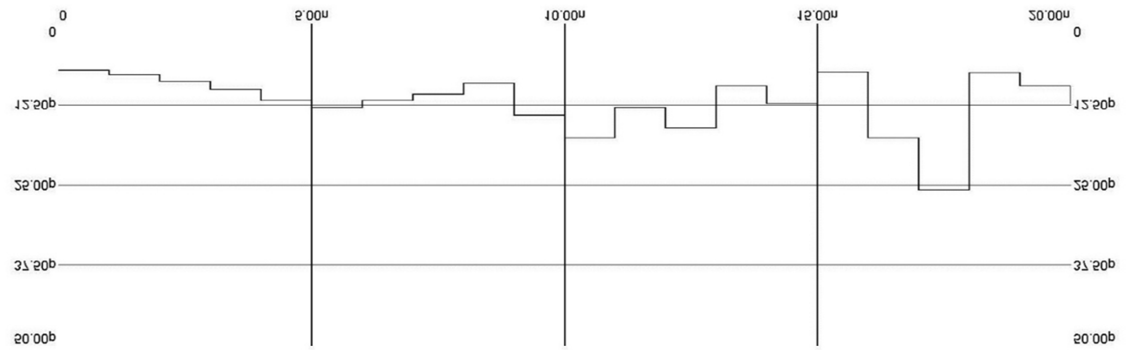

Fig 5(B

Fig 5a and Fig 5b: The change in capacitance C1 and C2 due to acceleration fed as an input to the sensing element.

8. Conclusion: The developed model of the MEMS capacitive accelerometer allows the designer to simulate the working of this design using computer-aided design. The changes in displacement, capacitance, frequency, change in output voltage of the sensor etc. Any discrepancies in the output can be very accurately studied and analyzed using this model. Furthermore, when the accelerometer is actually implemented, all the constraints can be pre-tested and implemented on this model to avoid a design flaw or changes in behavior of the device from unexpected data.

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