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Characterization of Capacitive Comb-finger MEMS Accelerometers

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Abstract

This paper discusses various methods for testing the performance of MEMS capacitive comb-finger accelerometers manufactured by Sandia National Laboratories. The use of Capacitive MEMS devices requires complex circuits for measurement of capacitance. Sandia MEMS accelerometer's capacitance changes in a very small femto-farad (fF) range. The performance of accelerometer is tested using Analog Devices AD7747 sigma-delta capacitance to digital converter. The response of a MEMS capacitive accelerometer to various tests is useful for testing and characterization and investigate it's suitability for various applications

Keywords: *MEMS Capacitive Acclerometers*

1. Introduction

In the past two decades, various capacitive MEMS accelerometers have been widely commercialized. Capacitive sensing is one of the most popular sensing mechanisms of inertial sensors because it has the advantages such as low power consumption, low noise, low-cost and compatibility with IC fabrication technology. However, the effect of parasitic capacitance is one of the main concerns for this type of capacitive sensors. A capacitive comb-finger accelerometer has a series of interlocking fixed and movable fingers, which are attached to the proof mass to measure the specific force through a change in capacitance. When the external acceleration is applied, the gap between the fixed and moving fingers changes, which corresponds to change in differential capacitance. This change can be measured using a suitable electronic circuitry [1, 2]. The Sandia MEMS accelerometers are manufactured using CMOS SUMMiT V fabrication process. The devices fabricated using SUMMiT V are truly complex and more advance systems can be created using this technology [3]. The MEMS accelerometer is capable of sensing change in capacitance in femto-farad range. In this paper, change in capacitance is measured using the Analog Devices AD7747 evaluation board. The AD7747 is sigma delta capacitance to digital converter, which converts capacitive input signal into digital values. This capacitance to digital converter is specifically designed for capacitive sensors [4].

2. Sandia Laboratories Capacitive MEMS Accelerometer

The Sandia laboratories MEMS accelerometers are manufactured using CMOS SUMMiT V fabrication process. It is a five-layer polycrystalline silicon surface micromachining process With the SUMMiT V process; more advanced, complex and flexible systems can be created at low-cost. Figure 1 shows the magnified view of a Sandia comb-finger accelerometer structure [3].

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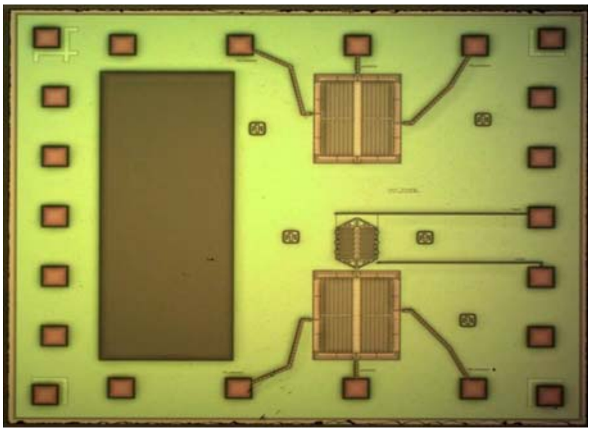

Figure 1. Sandia Capacitive MEMS accelerometer structure

3. Mechanical Sensitivity of Sandia Accelerometer

MEMS accelerometer sensitivity is an important design parameter. Sensitivity is the ratio of change in electrical signal (output) to change in physical signal (input). A spring mass model is used to model physical motion of accelerometers. For Sandia accelerometer, total sensitivity is a product of mechanical sensitivity and electrical sensitivity.

Mechanical sensitivity has the unit of displacement per unit gravitational acceleration (meters/g). Mechanical modeling can be studied by understanding spring mass model for a genericaccelerometer as shown in Figure 2 [5, 6].

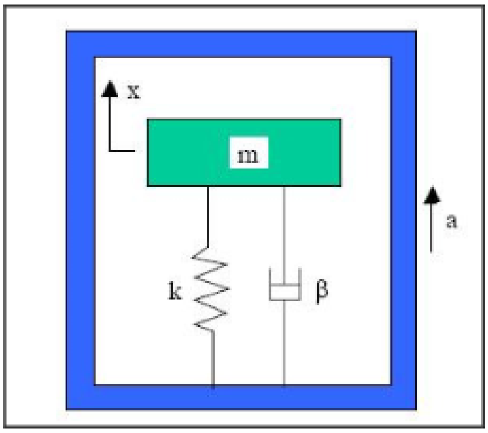

Figure 2. Sandia Capacitive MEMS accelerometer structure [6]

Figure 3 shows four beam folding structure of Sandia device. The accelerometer silicon proof mass is designated “m” and is suspended by a spring “k” to a frame. The spring operation follows the Hooke’s law, which contains the following relationship between the spring displacement and the force F [5, 6];

$$F = kx \tag{1}$$

Where k is the spring constant and is the displacement of the mass (m). From Newton’s law,

$$F = ma \tag{2}$$

Eq. [1] and [2] can be equated to get themodified equation

$$x = \frac{ma}{k} \quad (3)$$

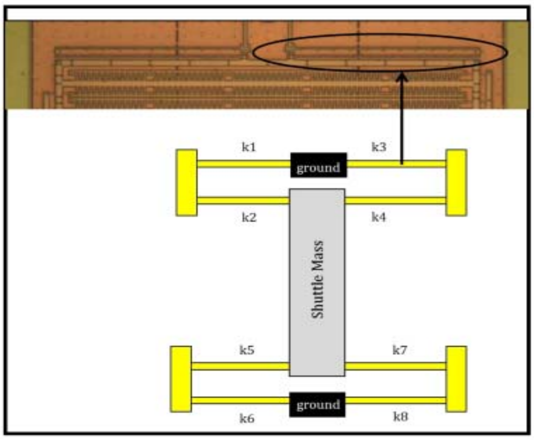

Figure 3. Sandia Capacitive MEMS accelerometer structure [6]

The beam springs, which are fixed at one end behave very much like a double cantilever beam. Figure [6] depicts the movement of such a beam, fixed at one end and moving along the rollers at the other.

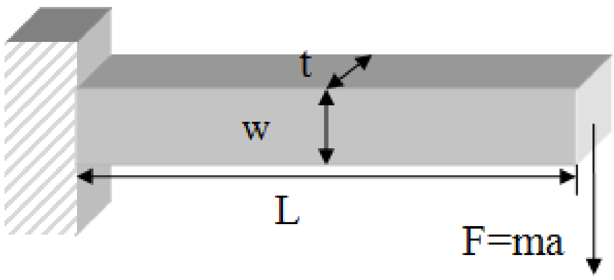

Figure 4. Cantilever beam movement with one rolling beam end [5]

For this particular geometry of the comb finger accelerometer, the spring constant K_{beam} is calculated using Eq. (4)

$$\boldsymbol{K_{beam}} = \frac{\mathbf{12}\boldsymbol{EI_b}}{\boldsymbol{L^3}} \quad (4)$$

whereI_b is the moment of inertia of the beam:

$$I_b = \frac{tw^3}{12} \quad (5)$$

The entire accelerometer would have four such folds, thus we have total spring constant of the whole accelerometer K_{System} is calculated using Eq. (6)

$$K_{System} = k_{fold1} + k_{fold2} + k_{fold3} + k_{fold4} = 4k_{fold1} \quad (6)$$

The system can be redrawn with spring mass system model as shown in Figure 2. Using Eq. (3) mechanical sensitivity can then be calculated when 1 g (9.8$\boldsymbol{m/s^2}$)is applied to system.

$$\boldsymbol{s_{Mech} = \frac{m * g}{K_{System}}}$$

$$s_{Mech} = \frac{1.17E{-}17[kg] * 9.8m/s^2}{0.554\ N/m} = 0.0206\ \mu m/g \quad (7)$$

where m is the value of accelerometer proof mass and g is gravitational acceleration. K_{system} is the spring constant or stiffness for the system [6].

4. Electrical Sensitivity of Sandia Accelerometer

The equation of capacitance shown below is dependent on the displacement between the two plates, which is the basis for using capacitive comb-finger accelerometer thus it is sometimes called electrostatic accelerometer [5].

$$C = \frac{\varepsilon_O \varepsilon_r A}{d} \quad (8)$$

Where ε_r is the dielectric constant between the plates, ε_o is the electric constant, A is the area of the two plates and d is the distance between the two plates.

Figure 5 [5] shows the proof (shuttle) mass sitting between the fixed fingers with no displacement. $C_1$is the capacitance of left side and C_2 is the capacitance of right side.

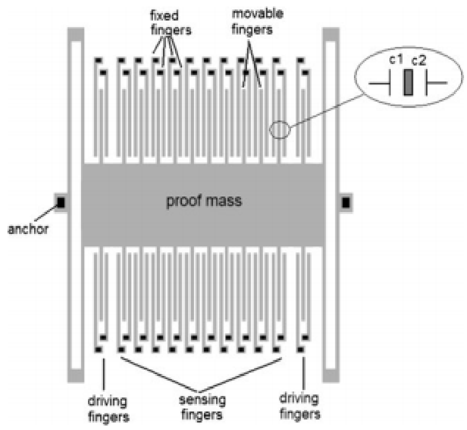

Figure 5. Capacitive interaction between movable and fixed fingers [5]

When there is no acceleration then differential capacitance is zero but when proof mass moves in the direction of acceleration, one capacitance will be larger than the other resulting in non-zero reading of the differential capacitance as shown in Figure 6 and Figure 7 [5]. Each Capacitor can be seen as capacitive reactance so the voltage difference equates the difference between the voltage drops across each capacitor. The magnitude of the voltage difference is proportional to the magnitude of the capacitance change [5]

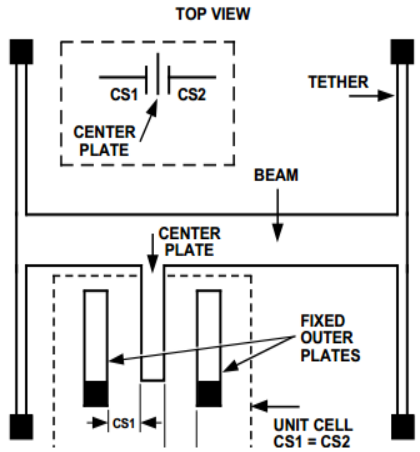

Figure 6. Capacitive fingers at rest [5]

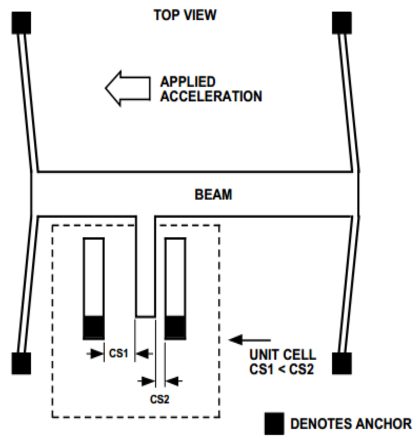

Figure 7. Movement of fingers when acceleration is applied [5]

The electrical modeling involves measuring the difference in capacitance to be simplified by creating all electrodes with the same area. C_1andC_2can be used to determine the output of the accelerometer circuit. For testing point of view, the accelerometer can be seen electrically as a capacitive voltage divider as shown in Figure 8 [1, 7]. For this circuit,

$$V_o = -V_s + \frac{C_1 + C2}{C_1 - C2}(2V_s) \quad (9)$$

$$V_o = \frac{C_1 - C2}{C_1 + C2}V_s \quad (10)$$

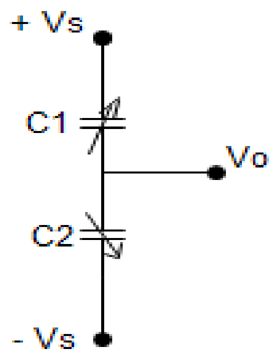

Figure 8. Circuit Model for Capacitive Voltage Divider [7]

The electrical sensitivity of the comb-finger incorporates both types of electrode movements lateral and transverse as shown in Figure 9 and Figure10 [6].

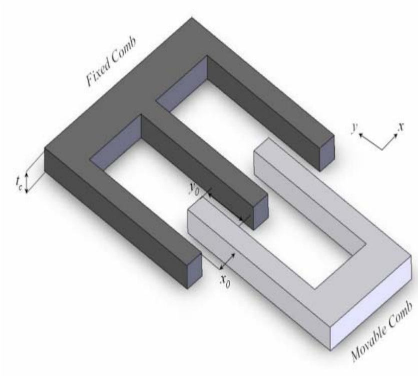

Figure 9. Electrode movements of comb-fingers [6]

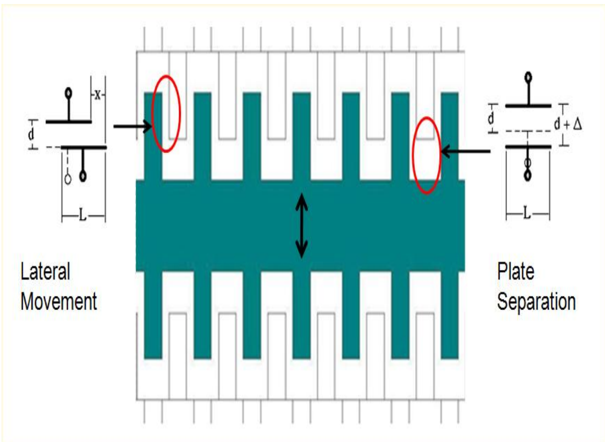

Figure 10. Electrode movements of comb-finger schematic [6]

Electrical sensitivity is the change in capacitance is due to change in displacement. The electrical sensitivity due to lateral movement is given in Eq. (11),

$$\frac{\Delta C}{\Delta x} = \frac{2\varepsilon N_1 t_f}{d_{01}} \quad (11)$$

The total electrical sensitivity has to take into account the plate separation so equation for total electrical sensitivity is given in Eq. (12),

$$s_e = \frac{\Delta C}{\Delta x} = \frac{2\varepsilon N_1 t}{d_{01}} + \frac{2\varepsilon N_2 tw}{{d_{o2}}^2} \quad (12)$$

The second term in [Eq.13] which is plate separation term in can be neglected if $\Delta x \ll d_o$ and because d_{02} is a large value compared to d_{01} and it is squared which makes the second term small compared to the first term. The total electrical sensitivity for Sandia comb-finger accelerometer is calculated as follows [5, 6];

$$S_{Elec} = \frac{2\varepsilon N_1 t_f}{d_{01}} \quad (13)$$

$$S_{Elec} = \frac{2(8.86\mathrm{e}-12\ \mathrm{F/m})(1080\ \mathrm{fingers})(4.5\mathrm{e}-6\ \mathrm{m})}{(1.25\mathrm{e}-6)\ \mathrm{m}}$$

$$S_{Elec} = 68.9\ \mathrm{fF/\mu m} \quad (14)$$

5. Total Sensitivity

Total sensitivity (S_T) of the Sandia accelerometer is the product of mechanical sensitivity (S_M) and electrical sensitivity (S_E) [5, 6].

$$\boldsymbol{S_{Total}} = (\boldsymbol{S_{Mech}})\ (\boldsymbol{S_{Elec}})$$

$$\boldsymbol{S_{Total}} = (\boldsymbol{S_{Mech}})\ (\boldsymbol{S_{Elec}}) = \left(\mathbf{.021}\frac{\boldsymbol{\mu}\mathbf{m}}{\mathbf{g}}\right)\ \mathbf{x}\ (\mathbf{68.9\ \ fF/\boldsymbol{\mu}m})$$

$$S_{Total} = 1.43\ \mathrm{fF/g} \quad (15)$$

To prevent the device from damage it was necessary to know the range of the accelerometer before performing any test. Mechanical and electrical sensitivity of Sandia accelerometer is known. These parameter values are mentioned in Table 1. The range of accelerometer can be found using Eq. 16 and Eq. 17.

Range of Sandia accelerometer = $\frac{Distance\ between\ fingers}{Mechanical\ Sensitivity}$

$$= \frac{1.25\ \mu m}{0.0206\ \mu m/g} = 60.6796\ \mathrm{g} \quad (16)$$

But for the factor of safety actual range of Sandia accelerometer is considered as,

$$\left[\left(\frac{1}{10}\right) * (60.6796)\right] = 6g\ approximately \quad (17)$$

Table 1. Design Parameter values of the Sandia accelerometer [5]

Parameters	Value
Mechanical Sensitivity	0.0206 $\mu m/g$
Electrical Sensitivity	68.9 $fF/\mu m$
Gap between comb-fingers	1.25 μm

6. Analog Devices AD7747 Evaluation Board

AD7747 is a high resolution, 24 bit sigma delta capacitance to digital converter. It is designed for single-ended or differential capacitive sensors with one plate connected to ground. It also has tolerance of parasitic capacitance to ground up to 60pF. The capacitive accelerometer input is connected to the inputs on a board and the required operational settings can be loaded through evaluation board and supported software though computer interfacing.

The AD7747 core as shown in Figure 10 is a high precision converter consisting of a second-order sigma-delta modulator and a third order digital filter. It works as a CDC (Capacitance to Digital Converter) for the capacitive inputs and ADC (Analog to Digital Converter) for the voltage input from or for the voltage from a temperature sensor. With the converter AD7747 also integrates multiplexer, an excitation source and CAPDACs (Digital to Capacitance converter) for the capacitive input. AD7747 supports I^2C compatible serial interface, a control and calibration logic. AD7747 is not factory calibrated for capacitive offset so its user's responsibility to calibrate the system capacitive offset in the application [4, 9].

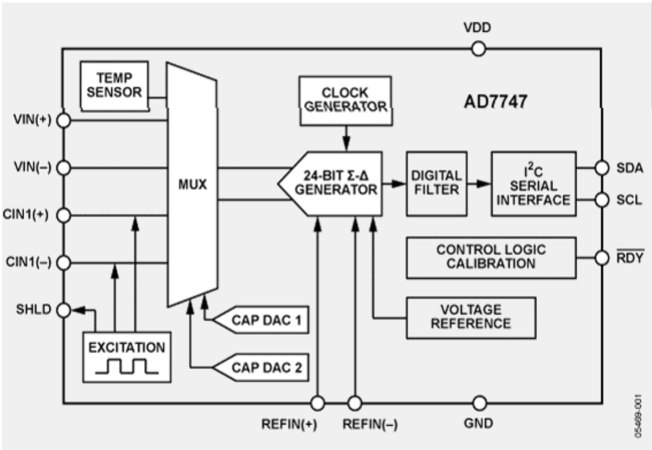

Figure 10. Functional block diagram of AD7747 board [8]

7. Test and Measurement

It is necessary to check the packaged MEMS devices before actual testing.

8. Continuity Test

A primary method of testing the MEMS device is to check the discontinuity between fingers and different layers. This test provides information about proper structure of fingers and good devices can be easily sorted out.

9. LCR Meter Test

Testing a damaged unit could result in inaccurate data so to quantify viable test accelerometer without any risk was possible with a LCR meter. (Inductance (L), Capacitance (C) and Resistance (R)). As Sandia accelerometers should read very small capacitance with very high resistance/impedance, it is assumed that if both the sides of device read small capacitance with high resistance then it is good for further testing. The reasoning here is that if the proof mass and comb-fingers are connected on the inside, it will lose its capacitance and it will show drop in resistance over that side.

10. Tip Test

The simple way to see if capacitive accelerometer is sensing a difference in capacitance is a Tip Test. To perform this test first capacitance is measured when accelerometer is at rest, then it is positioned in such a way that its sensitive axis is perpendicular to the earth gravitation vector. The difference in acceleration can be observed and capacitance measurement is done AD7747. The test setup is shown in Figure 11 (when accelerometer is at '0' g acceleration) and 12 (when accelerometer is at '+1g' and '-1g' acceleration), respectively.

Offset is nothing but nulling zero error or bias and scale factor or sensitivity of an accelerometer is the ratio of the sensor electrical output to mechanical input typically rated in pF/g. These two are fundamental parameters to specify a sensor and form the basis for further detailed performance testing.

The test data is collected for each position when accelerometer is at rest, at +1g and -1g position. The offset and Scale factor values are calculated from that data; using following equation 18 and equation 19.

$$\text{Offset} = [(1g) + (-1g)] / 2 \quad (18)$$
Offset = 8.19604 pF

$$\text{Scale factor} = [(1g) - (-1g)] / 2 \quad (19)$$
Scale factor = 4.20076E-07 pF/g

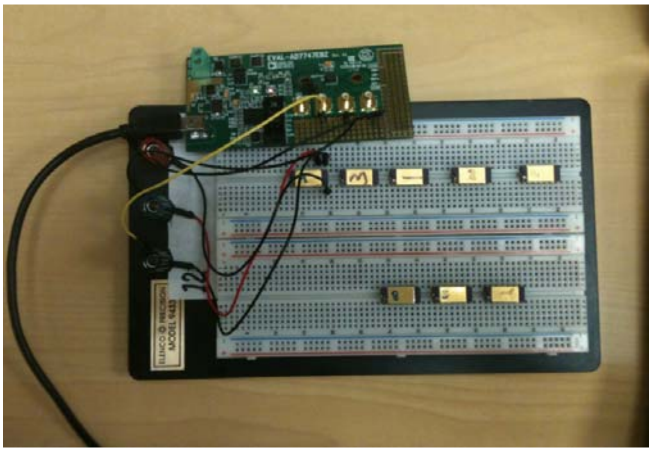

Figure 11. Test set up for Vibration test at rest

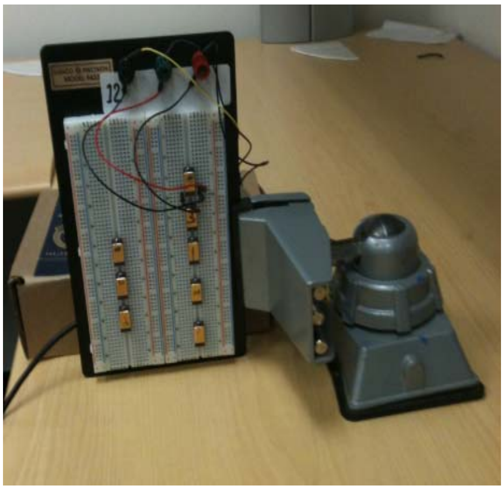

Figure 12. Test set up for Vibration test at 1g

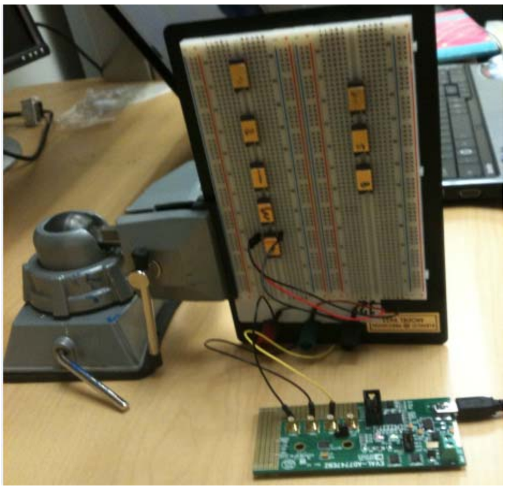

Figure 13. Test set up for Vibration test at -1g

11. Thermal Test

The thermal test is designed to determine the thermal stability characteristics of accelerometer at particular temperature range. To avoid the risk of damage temperature was slowly increased from for this test. Figure 11 shows thermal test result for Sandia MEMS accelerometer. The trend of decreasing capacitance with increase in temperature is observed from the test result.

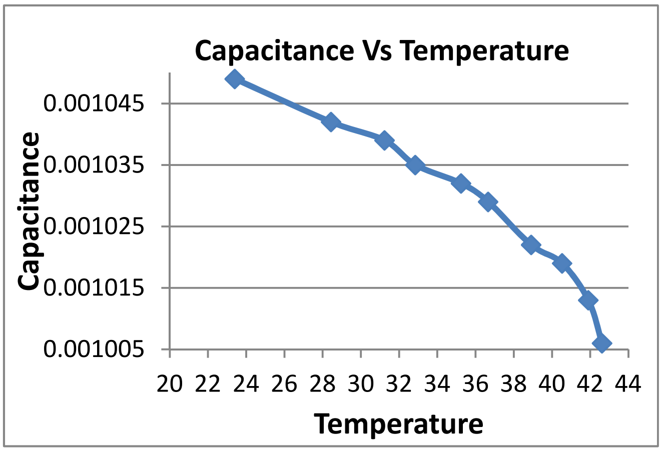

Figure 14. Thermal plot for Sandia 14 pin accelerometer

From Figure 14, the Thermal drift (max) for accelerometer = 0.18% of reading/Deg. Celsius

12. Hysteresis Test

A sensor (accelerometer) should be capable of following changes in capacitance (input parameter) regardless of which direction the change is made and hysteresis is the measure of this property. To perform this test temperature was slowly increased and then decreased from room temperature to the highest temperature which device could sustain. Hysteresis is expressed as % of FSO. The hysteresis plot is shown in Figure 15. From Figure 15, hysteresis (max) is = 0.58% of reading

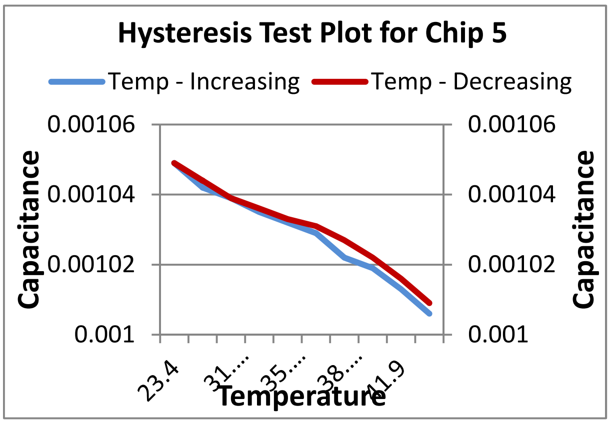

Figure 15. Hysteresis plot for Sandia 14 pin accelerometer

13. Vibration Test

To conduct vibration test, accelerometer is mounted on shaker table and acceleration is increased and change in capacitance is observed at different acceleration values. To avoid device damage, vibration test is performed at 0.5g, 1g and 1.5 g accelerations. The vibration test set up is shown in Figure 16 and test results are shown in Figure 17.

Figure 16. Test set up for Vibration test

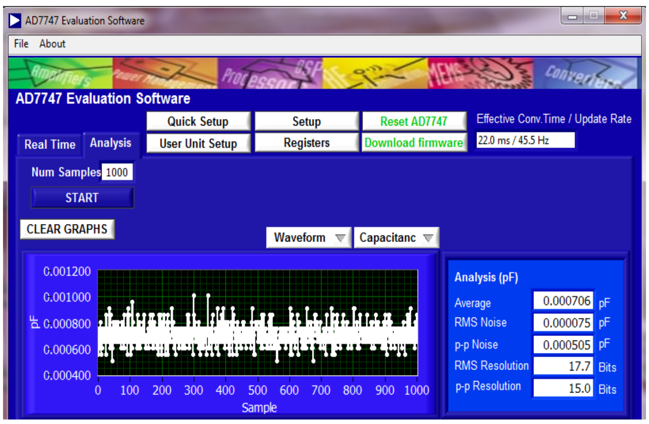

Figure 17. Vibration test result for Sandia accelerometer at 0.5g acceleration

14. Noise Analysis using Allan Deviation

Allan deviation is a statistical analysis method that can be used to measure noise error and bias stability in inertial sensors. It can identify and measure the magnitude of each type of noise error in a signal of mixed noise. The slope at different points in the plotted Allan deviation graph determines the different noise errors. The MEMS accelerometer noise typically consists of the following terms, which can be represented using Allan variance plots [10].

- Quantization noise: It is one of the errors introduced into an analog signal by encoding it in digital form. That noise is caused by the small differences betweenthe actual amplitudes of the points being sampled and the bit resolution of the analog-to-digital converter. The quantization noise is represented by a slope of -1 in a log-log $\sigma(\tau)$versus τ.
- Angular random walk: This is an angular error process, which is due to white noise in angular rate. ARW is a high frequency noise and it can be observed as the short- term variation in the output. It is represented by a slope -1/2 in log-log $\sigma(\tau)$versus τ.
- Bias instability: The bias stability is also known as flicker noise. This is a low frequency bias fluctuation in the measured data. Bias instability determines the best stability that could be achieved with fully modeled sensor.

Figure 18 to Figure 20 shows Allan deviation, Quantization noise and Angular random walk plots for Sandia 14 pin accelerometer. The ARW can be determined from this plot as the Allan deviation corresponding to τ = 1 sec, is approximately 4.1E-6. The bias stability of the accelerometer is the minimum Allan deviation approximately 0.2E-6.

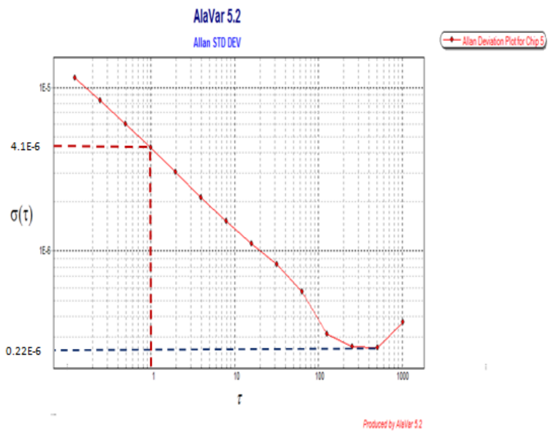

Figure 18. Allan deviation plot for Sandia 14 pin accelerometer

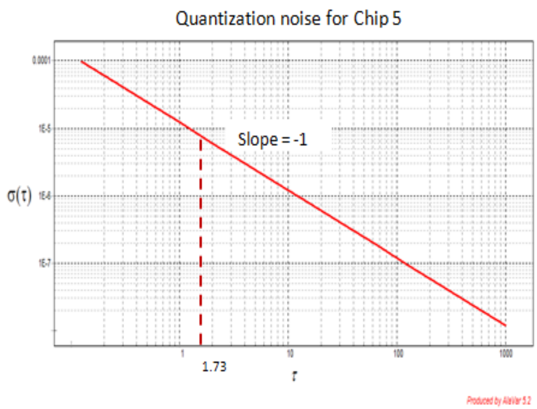

Figure 19. Quantization noise plot for Sandia 14 pin accelerometer

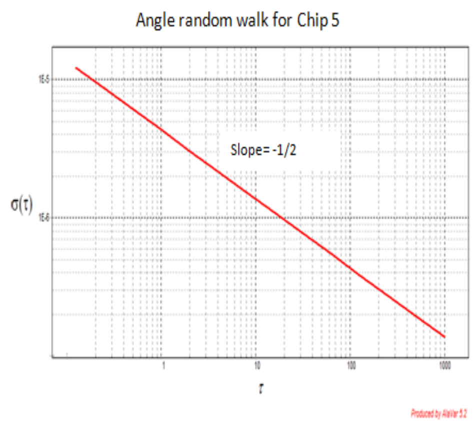

Figure 20. Angular random walk plot for Sandia 14 pin accelerometer

15. Conclusions

In this paper, exhaustive methods of testing micro-machined capacitive comb-finger accelerometer are discussed. The performance of Sandia capacitive comb-finger MEMS accelerometer is studied under various conditions. The change in capacitance is measured by using an Analog devices AD7747 capacitance to digital converter. This framework and process of analysis and testing using various design parameters is helpful for characterization of any MEMS capacitive sensor. The major findings of this research are mentioned in Table 2.

Table 2. Measured parameters values of the Sandia accelerometer

Type of the test performed	Measured parameter	Measured value of the parameter
Thermal test	% Thermal drift	0.21
Hysteresis test	% Hysteresis error	0.48
Vibration test	p-p noise 1g acceleration	0.000505pF
Bias stability	fF	0.2E-6

Acknowledgments

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