A Capacitive ID-Sensor with Internal PUF

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***Abstract*—The paper describes a sensor that offers a unique characteristic. It is impossible to duplicate the sensor because it belongs to devices with a Physical Unclonable Function (PUF). The sensor detects mechanical parameters. It has a capacitive electrode structure (dual electrode configuration) and can transform the movement of a membrane filled with conductive steel balls into a capacity change. Since the steel balls are randomly distributed, the sensor is unique and unclonable. The sensor has a large offset (fixed) capacity along with a variable capacity. Only the variable capacity varies with measured quantity. This paper presents an electrical equivalent model of the sensor. Detailed analysis of the model shows, the ground plane introduced to reduce the offset capacity degrades the sensitivity. Therefore, a new differential capacitive electrode structure is proposed. It nullifies the unwanted offset capacity and provides a sensor output of only the variable capacity. The new sensor design is verified using finite element analysis software COMSOL Multiphysics. Different steel ball distributions (i.e. sensors) have been assumed to study their influence on the sensor output. It was possible to prove the uniqueness of each senor by different output signals for the same excitation. Results are very promising in view of the application of such sensors in Identity-systems (ID-systems).**

***Index Terms*—sensor, capacitive, steel balls, PUF, identification, modeling, FEM, acceleration**

I. Introduction

During the last decade, advancement in microfabrication technology enabled the development of sensors with high sensitivity, small size and low fabrication costs. Currently, sensor technology is almost shrinking and cost reduction. One interesting and less investigated area is sensors with a nature like behavior. These sensors offer a unique characteristic since they are physically slightly different. Due to that, it is possible to identify each sensor as one original. In the field of identification, this originality is a basic requirement to obtain unique assignments. This uniqueness bases on a so-called Physical Unclonable Function (PUF). A PUF-device is a transducer that generates a unique response at an external excitation or a challenge [1]. Characteristics of each PUF-device are measurably different from others. In addition, the responses of PUF-devices are difficult to model and duplicate. PUF-devices could be used in different applications. Sensors with unique characteristics are exploited in the field of biomimetic sensors [2]. Nature uses arrays of receptor elements with unique characteristics to gather information. The brain of highly developed animals or humans can identify the receptor elements due to their uniqueness [2], [3]. As the frequency characteristic of each receptor element differs, the dynamic range of such arrays is also broader [4]. Biomimetic sensors use this functionality of natural sensors [2], [5]. Another application of PUF-devices are sensor networks [6]. Presently, cryptographic modules additionally attached to sensor nodes provide network security. However, this architecture is vulnerable to direct physical attack on the sensor. PUF-device can provide security at sensor level [1]. In the field of authentication, only real PUF-devices show a unique and unclonable characteristic. The output of such a device can serve as a digital signature.

A sensor with such a PUF characteristic for measuring mechanical parameters has been developed and reported in [6]. The sensor was fabricated by means of a simple, cost effective and rapid prototyping process. Fig. 1 shows the 2D-scheme of the sensor. In this article, therefore sensors are designated with this characteristic as ID- sensors.

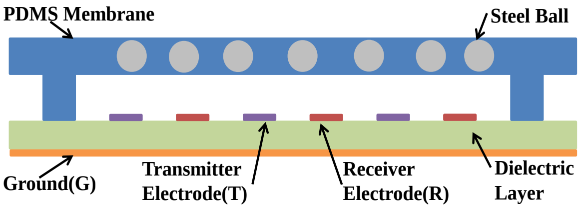

Figure 1. 2D scheme of the ID-sensor for measuring mechanical parameters [1].

The sensor uses a membrane of PDMS filled with conductive steel balls as structural element. A capacitive electrode formation below the membrane, converts the movement of the structural element into a change in capacity. The conductive steel balls are randomly distributed. Hence, the distribution of the mass of structural element is unique. Each steel ball takes on a floating potential and acts as a floating electrode. The field pattern is also unique for different sensors. Unique field pattern and mass distribution offer a unique output characteristic for each sensor. Initially, an interdigitated electrode design had been proposed [2]. Later, an improved electrode shape (interdigitated single side arranged electrode – ISSAE), which increases the sensitivity, was developed [7]. The new electrode shape also reduces the offset capacity. The sensor was tested under pressure, tilt and acceleration loads. Test results

Manuscript received August 23, 2016; revised November 30, 2017.

doi: 10.18178/ijmerr.7.2.202-207

show that the sensitivity of the sensor is comparable with sensors available on the market [8].

The ISSAE ID-sensor has a large fixed capacity, called offset capacity, along with variable capacity [7]. Only the variable capacity varies at changing excitations. The offset capacity leads to a large unwanted capacity in the sensor output. An ID-sensor with a differential electrode arrangement instead of nullifies the offset capacity and is the basis of this paper. The differential electrode sensor possesses of two similar ISSAE-structures. Lower and upper electrode structures transform the movement of the conductive membrane located between both into a change of the capacity values. The variable capacity of the upper and lower electrode structure behaves in a push pull manner, i.e. when the capacity of the lower structure increases, the capacity of upper structure decreases and vice versa. Offset capacities are equal and fixed for both upper and lower structures. The differential principle cancels the fixed offset capacities and adds the variable capacities.

The paper is organized as follows. An electrical equivalent model of the ISSAE sensor is presented in section 2. The effect of a ground plane on the sensor sensitivity and offset capacity is analyzed using a model developed for the sensor. In section 3, design details of differential capacitive ID-sensor will be discussed. Finally, a finite element analysis of the sensor and results of the simulation are given in section IV.

II. Modeling and Analysis of the ISSAE Identification-Sensor

A. Modeling of the Sensor

In order to analyze the ISSAE-sensor, an electrical equivalent model of the sensor was developed. Fig. 2 shows a scheme of a sensor element, assuming the influence of just one steel ball.

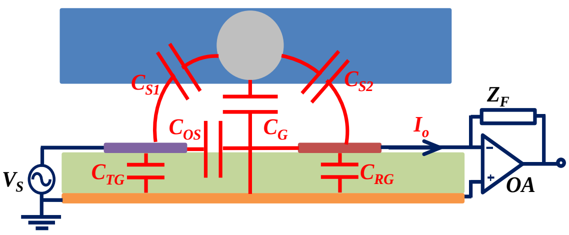

Figure 2. Detailed diagram of the capacitive sensor for a pair of electrodes one steel ball; variable capacities: C_{S1}, C_{S2}, C_G; fixed capacities C_{OS}, C_{TG}, C_{RG}.

To simplify the sensor model, only a pair of electrodes (transmitter -T, receiver-R) is considered. The sensor capacity depends on the type of capacity measurement setup. In this paper, we consider just a setup with a dual electrode. It offers a better performance when both electrodes are accessible for the measurement [9]. Around an Operational Amplifier (OA) a voltage source (V_S) and a Current to Voltage Converter (I-V) are arranged. They are belonging to the dual electrode measurement setup. When the transmitter electrode (T) is excited with a voltage V_S, an electric field occurs from T to the receiver R. If a mechanical force acts on the membrane, it starts to move. A movement of the PDMS membrane filled with conductive steel balls modifies the electric field pattern and changes the capacity between the electrodes T and R. The sensor capacity C_S is a combination of different capacities between T and R. Fig. 2 shows the capacities that contribute to C_S. The PDMS membrane is a dielectric insulator. Normally, the steel balls take on a floating potential. Therefore, one can consider them as floating electrodes (F). The capacities C_{S1} and C_{S2} represent capacities between terminals T and F, and terminals R and F, respectively. C_{OS} is the capacity between T and R through the dielectric layer. The ground plane (G) takes also some of the electric field lines from T to G. This reduces the value of C_{OS}. Additional exist some parasitic capacities, too. C_G is the capacity between a steel ball (F) and the ground G, C_{TG} is the capacity between terminal T and the ground. C_{RG} is the capacity between R and the ground. A membrane movement changes the values of C_{S1}, C_{S2} and C_G. A movement towards the ISSAE increases C_{S1}, C_{S2} and C_G, and vice versa. The values of these capacities depend on the position and concentration of the steel balls. As the steel balls are randomly distributed, one can expect different values for different sensors. Other capacities like C_{OS}, C_{RG} and C_{RT} are constant for a fixed ISSAE structure. The total sensor capacity C_S can be estimated by measuring the current I_o at terminal R. The I-V converter transforms I_o to a corresponding voltage.

B. Y-Δ-transformation and Capacity Relations

Fig. 3a) shows an electrical equivalent model of the sensor with an ISSAE setup. Unfortunately, the variable capacities C_{S1}, C_{S2} and C_G form a star network. Calculations of star shaped arrangement like this are difficult. A mathematical solution can be a Y-Δ transformation.

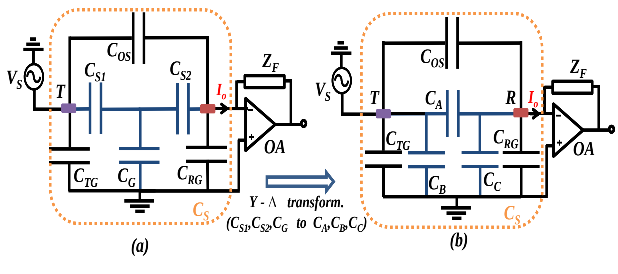

Figure 3. (a) Electrical equivalent model of the ID-sensor setup b) Star-Delta transformation applied to electrical equivalent model.

Fig 3(b) shows a resulting circuit, when such a transformation is applied. Instead of the original capacities on gets now the spare capacities C_A, C_B, and C_C. Based on the original values, one can now calculate the values of the spare capacities.

$$C_A = \frac{C_{S1} C_{S2}}{C_{S1}+C_{S2}+C_G} \quad (1)$$

$$C_B = \frac{C_{S1} C_G}{C_{S1}+C_{S2}+C_G} \quad (2)$$

$$C_C = \frac{C_{S2} C_G}{C_{S1}+C_{S2}+C_G} \quad (3)$$

From Fig. 3b) one can see C_{TG} and C_B are in parallel to the excitation Voltage V_S. The source supplies the capacities C_{TG} and C_B with a corresponding current and hence, the receiver current, I_o is independent of the capacities C_{TG} and C_B. Similarly, the capacities C_{RG} and C_C are connected across the inverting and the non-inverting terminals of the I-V converter. As the inverting terminal of the I-V converter is at floating ground potential, i.e. grounded and the non-inverting terminal is grounded too, no current flows through C_{RG} and C_C. Under these conditions, the sensor capacity C_S can be rewritten as

$$C_S=C_{OS}+C_A \tag{4}$$

After substituting (1) in (4) one achieves:

$$C_S=C_{OS}+\frac{C_{S1}C_{S2}}{C_{S1}+C_{S2}+C_G} \tag{5}$$

From (4), the sensor capacity is a parallel combination of the fixed offset capacity (C_{OS}), and a variable capacity, C_A. It varies with the membrane movement and contains information about measuring parameters. C_{OS} is the fixed unwanted capacity. Their value is constant for a given electrode structure. The value of the offset capacity can be reduced by thinning the dielectric layer (see Fig.2). Such a reduction even reduces the distance between the transmitter T and ground G. In this case, more electric field lines contribute towards the ground terminal. Hence, the fixed capacity C_{OS} decreases while the capacities C_{TG} and C_{RG} increase. Fortunately, C_S decreases too because it is independent of C_{TG} and C_{RG}. On the other hand, a thinner dielectric layer also reduces the distance between the conductive balls and the ground (G). This increases the capacity C_G. To study the influence of C_G on C_S, it is assumed that each steel ball has exactly the same distance to T and to R. In that case is C_{S1} equal to C_{S2} and the variable spare component of the capacity C_A can be written as

$$C_A=\frac{C_{S1}^2}{2C_{S1}+C_G} \tag{6}$$

The value of C_A increases with an increase of C_{S1}, but decreases with an increase of C_G. The movement of the membrane either increases or decreases both capacities C_{S1} and C_G simultaneously. Hence, C_G reduces the sensitivity of the sensor. Equation (6) shows that the effect of C_G on C_A can be reduced if the value of C_G is low. To decrease $C_{G,}$ the thickness of the dielectric layer (see Fig. 1) needs to be reduced. Unfortunately, this increases the unwanted offset capacity C_{OS}. Hence, in an ISSAE ID-sensor, the reduction of the offset capacity leads simultaneously to a reduction of the sensitivity of the sensor.

C. *Differential Capacitive ID-sensor Design*

All different approaches to increase the sensor signal and to reduce the offset are not very promising. Therefore, a new approach could help to overcome all existing problems. This new approach bases on a differential capacitive design. Such a design nullifies the offset capacity and improves the sensitivity of the sensor. Fig. 4. shows the scheme of such a sensor solution.

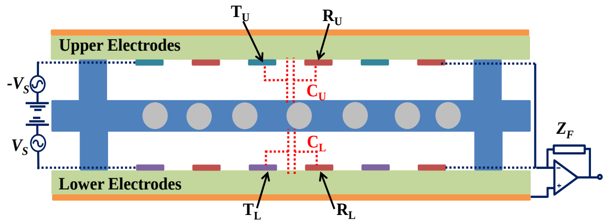

Figure 4. 2D-scheme of the unique differential capacitive sensor.

Two separate electrode structures, an upper and a lower, are able to convert the movement of the membrane into changing capacity values. The capacity plates T_L and R_L form now a lower ISSAE-structure. T_U and R_U form the upper ISSAE-structure. The capacity between T_L and R_L becomes the sign C_L and that one between T_U and R_U becomes the sign C_U, respectively. The membrane is assumed to be exactly in the middle between the two ISSAE-boards. Based on equation (4), one can write for the capacities of the lower and the upper electrode structure:

$$C_L=C_{OSL}+ C_{AL} \tag{7}$$

$$C_U=C_{OSU}+ C_{AU} \tag{8}$$

C_{OSL} and C_{OSU} are the offset capacities and C_{AL} and C_{AU} are the variable parts of the capacities of the lower and the upper electrodes, respectively. When the membrane moves towards the lower electrode, C_L increases, C_U decreases and vice versa. C_L and C_U can be further expressed as

$$C_L=C_{OSL}+ C_{AL}\pm \Delta C_{AL} \tag{9}$$

$$C_U=C_{OSU}+ C_{AU}\mp \Delta C_{AU} \tag{10}$$

ΔC_{AL} and ΔC_{AU} are the changes of the capacity values due to membrane movement. Under the assumption a signal V_S excites T_L and $-V_S$ excites T_U the receiver current, I_o is proportional to $C_{SL} - C_{SU}$. In this case, one can define C_S as:

$$C_S = (C_L- C_U)$$
$$= (C_{OSL}- C_{OSU})+ (C_{AL}-C_{AU}) \pm(\Delta C_{AL}+\Delta C_{AU}) \tag{11}$$

If the dimensions of the upper and the lower structures are equal, this condition leads to following relations:

$$C_{OSL} = C_{OSU} \tag{12}$$

$$C_{AL} = C_{AU} \tag{13}$$

Finally, one can find the following relation for the capacity value of the sensor:

$$C_S=\pm (\Delta C_{AL}+\Delta C_{AU}). \tag{14}$$

From equation (14), one can conclude the sensor with differential electrode structure cancels the unwanted offset capacities. The sensor capacity C_S bases only on the variable components. As C_S is independent of C_{OS}, the thickness of the dielectric layer plays no more an influencing role. A large thickness of this layer reduces the effect of C_G and helps to improve the sensitivity of the sensor. For small movements of the membrane one can assume:

$$\Delta C_{AL} \approx \Delta C_{AU} \quad (15)$$

This leads again to a simplification and one can write:

$$C_S = \pm 2\Delta C_{AL} \quad (16)$$

The differential electrode PUF offers twice the sensitivity compared to that of dual electrode individualized sensor.

III. Finite Element Analysis

The behavior and performance of the differential capacitive ID-sensor has been analyzed using the commercially available Finite Element Analysis (FEA) software COMSOL Multiphysics. The sensor transforms the movement of a membrane filled with conductive balls into a change of capacity. Modeling of the sensor requires solving of structural mechanics and electrostatics equations. COMSOL offers an electro mechanic module, which couples structural mechanics and electrostatics. This specific module is basis of the analysis. Details of the simulation and corresponding results will be discussed in the following sections.

A. *Thickness of Dielectric Layer*

In order to verify the developed electrical model and to find the influence of the ground plane on the sensitivity and the offset capacity of the sensor, a 2D structure of an ISSAE sensor is drawn in COMSOL Multiphysics. First, it was investigated how an external pressure affects the sensor behavior. Therefore, sensors with different dielectric thicknesses (D_t) of 0.1mm, 0.5mm and 1.0mm were studied. The pressure was applied in an order the membrane moves closer to the ISSAE. The normalized capacity (normalized to the capacity observed at p = 0Pa) found in the simulation, is plotted in Fig. 5.

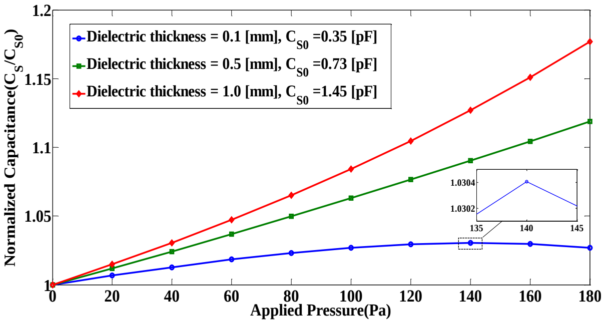

Figure 5. Normalized capacity recorded from the ID-sensor with dielectric thickness (Dt) 0.1mm, 0.5mm and 1.0mm for pressure load.

With increasing pressure, the capacity of the sensor increases, too. Individualized sensors with D_t 0.1mm, 0.5mm and 1.0mm show a sensor capacity of 0.35pF, 0.73pF and 1.45pF, respectively. Because of the low value of C_G, sensors with higher D_t offered higher sensitivity but unfortunately with a high value of the offset capacity, as expected. Above pressure values of about 140 Pa the sensor with D_t = 0.1mm shows a negative characteristic, i.e. the capacity starts to decrease with the pressure. An explanation of this effect is not as simple. An attempt bases on Figure 2. The movement of the membrane increases C_{S1}, C_{S2} and C_G. As long as D_t is low, the value of C_G is comparable higher as of sensors with thicker dielectrics (D_t = 0. 5mm and D_t = 1.0mm). Up to the applied pressure of 140Pa, the value of C_G is even though high. The capacities C_{S1} and C_{S2} are predominant and the change of current I_o (due to the movement of the membrane) is greater than changes of current through C_G.

With further pressure increase, the effect of C_G gets dominant. This drives more current to the ground plane and therefore decreases the output current I_o. This in turn reduces the capacity of the sensor.

B. *Identification of PUF*

The sensor with a differential electrode arrangement was also simulated. Sensor dimensions, selected materials and boundary conditions are given in Table 1. The improved electrode design reported in [7] is used for the upper and lower electrodes. To cancel the offset capacity, all dimensions of the upper and lower electrodes are similar.

TABLE I. Simulation Settings

	Material	**Electromechanical Module**		**Dimension cm**
		Domain	**Boundary**	
PDMS Membrane	PDMS	Linear Elastic Material, Electrical Material Model, Gravity		1.5(L) ×1.5(W) ×0.1(H)
PDMS columns	PDMS	Linear Elastic Material, Electrical Material Model, Gravity	Fixed Constraint	0.1(R) 0.05(H)
Electrodes (R,T,G)	Copper	Electrical Material Model	Terminal	Same dimensions in [1]
Conduct. steel balls	Steel AISI 4340	Linear Elastic Dielectric, Electrical Material Model, Gravity	Floating Potential	0.04(R)
Dielectric layer	FR4	Linear Elastic Dielectric, Electrical Material Mode, Fixed Constraint		1.5(L) ×1.5(W) ×0.05(H)

Since the distribution of the steel balls is different for different sensors, it is of importance to characterize different sensors by a simple parameter. In view of identification purposes, it is common to use the so-called Inter- and Intra-distance [10]. It describes the difference of the response value of similar devices for the same challenge. In this work, the Inter- and Intra-distance represents different capacity values of different sensors for the same excitation. The difference in sensors bases just on the random steel ball distribution, all dimensions and electrode arrangements are equal. Six sensor models SM_1-SM_6 with different steel ball distributions estimate the simulation. Figure 6 shows the steel ball distributions used in the simulations.

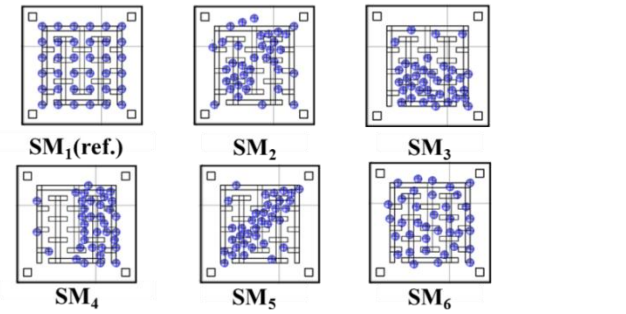

Figure 6. 2D scheme of the unique differential capacitive sensor.

SM_1 is the reference sensor. As basis, all simulation results are based on. Therefore, the steel balls are arranged evenly in SM_1 All other five models (SM_2- SM_6) balls possess of randomly distributed steel ball in the PDMS-membrane. The Inter- and Intra-distance of each sensor is calculated by comparing the capacity values of a certain excitation with the capacity values of sensor SM_1 at the same excitation.

C. Investigation of the Inclination Behavior

First, inclination changes should affect the values of the differential capacitive arrangement. If there are differences in the capacity levels for different sensors at equal angles of inclination, one can truly assume a PUF in each device. Tilting a sensor is comparable with a variation of gravity components. In order to simulate tilt along the X axis, the Z- and Y-components of the gravity load were set to -9.8*cosΘ and +9.8*sinΘ respectively. Θ represents the tilt angle. It varies from 0° to +180°. Fig. 7 shows the simulation of the movement of the membrane for different tilt angles (0°, 45°, 90°, 135°, 180°). Upper and lower electrode structures convert the position of the membrane into a regarding capacity. In the first row, the membrane deflects initially to the lower electrodes. When inclination occurs, the deflection decreases and shows a value of "0" at an angle of 90°. With further increasing angle the deflection turns the direction to the upper electrodes and reaches a maximum at an angle of 180°. The separate consideration outputs of the upper electrode and the lower electrode structure of sensor SM_1 deliver an inclination depending image of the reference (see Fig. 7).

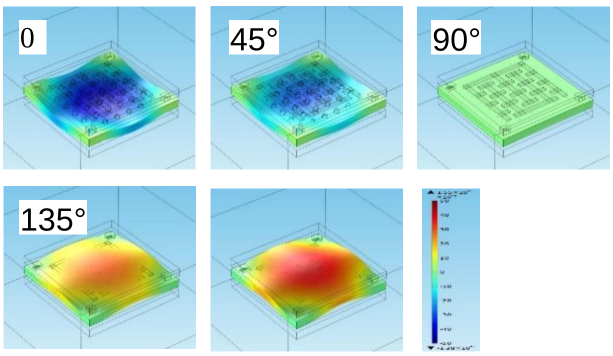

Figure 7. Displacement of the membrane filled with conductive balls for different tilt angles.

Both outputs vary in a push-pull manner. The lower transmitter T_L is supplied with a positive signal, while the upper transmitter T_U is excited with a negative signal. The receiver terminals (R) are at zero potential. The differential output recorded under these conditions is shown in Fig. 8. The dual electrode sensor has a fixed offset capacity of around 0.7pF. Then the differential measurement is carried out by simultaneously measuring lower and upper electrodes. The sensor with the differential electrode structure cancels the offset capacity. Further, with an additional electrode structure, the differential capacitive of the individualized sensor offers a higher sensitivity. The PUF-device with random steel ball distribution (SM2 – SM6) are also simulated. Differential outputs recorded from the sensors SM1 to SM6 are shown in Fig. 9. Because of different ball distributions, the output of each sensor is unique and different from other sensors.

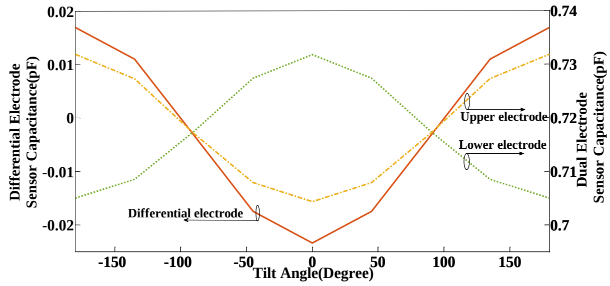

Figure 8. Output recorded from sensor SM1 for differential electrode and single electrode (upper and lower separately).

The measure of uniqueness, intra-hamming distance is calculated by taking the difference between sensor outputs and the reference sensor and plotted in Fig. 9. The value of hamming distance (= SMn-SM1) increases from zero to ±180° along with the sensor capacity.

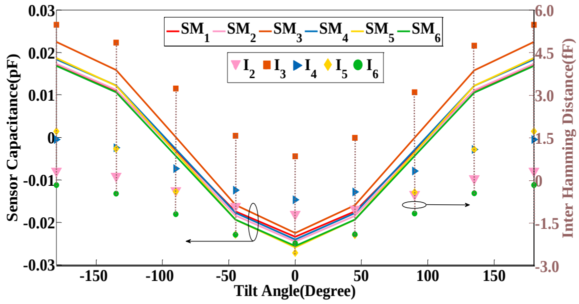

Figure 9. Simulation results recorded when a tilt load is applied to sensors with different steel ball distribution

D. Investigation of the Acceleration Behavior

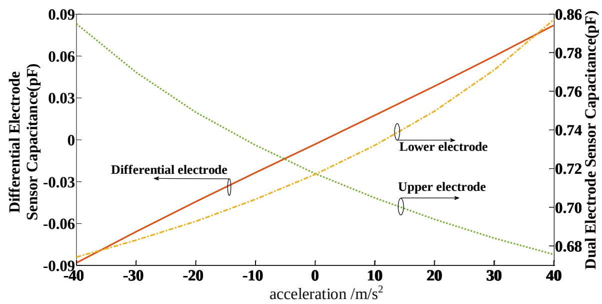

Figure 10. Sensor capacity recorded from SM1 for acceleration load in Z-axis. Acceleration varies from -40m/s2 to +40m/s2.

The differential capacitive ID-sensor is also simulated for acceleration along the Z-axis. An acceleration load is applied to the membrane. Outputs recorded with upper electrode, lower electrode and differential electrode structures are plotted in Fig. 10.

Acceleration in the +Z-axis direction moves the membrane towards the lower electrode, therefore the lower electrode capacity C_L (in Fig. 5) increases and the upper electrode capacity C_U decreases. When the acceleration is in Z-direction C_U increases and C_L decreases. The differential electrode nullifies the offset capacity and improves the sensitivity. Furthermore, for acceleration, the differential electrode measurement showed a better linearity. The six sensor models SM_1-SM_6 are also simulated for acceleration. Output recorded is plotted in Fig. 11. Again, the uniqueness of each sensor output is observed. The intra hamming distance is calculated and plotted in Fig. 11. The hamming distance increased with an increase of acceleration. The difference between the hamming distances among different sensors also increases with an increased acceleration. At higher accelerations, the membrane is closer to either the upper or lower electrode structure. The electric field intensity is higher near the electrodes. Hence, the uniqueness increases if the membrane filled with balls is closer to the electrode structures.

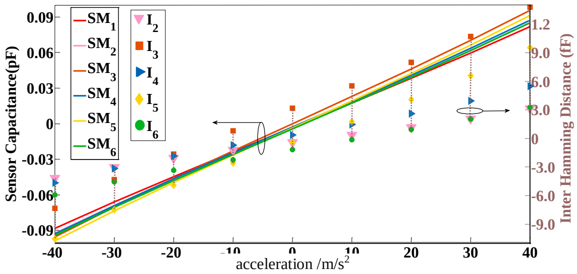

Figure 11. Sensor capacity for different accelerations in relation to SM_1.

IV CONCLUSION

A ID-sensor with a differential electrode structure is designed and details are presented in this paper. The electrical equivalent model of dual electrode ID-sensor shows that the ground plane introduced to reduce offset capacity reduces the sensor sensitivity. With two capacitive electrode structures and a differential capacitive measurement technique, the differential ID-sensor cancels the offset capacitance and provides an output, which only contains the variable component. The electrical equivalent model of the dual electrode sensor and the differential electrode sensor design is verified using Finite Element Analysis. The ID-sensor is simulated with six different steel ball distributions for tilt and acceleration. The uniqueness of each sensor is calculated in terms of inter hamming distance. Results show that a random distribution of balls can introduce measurable unique characteristics. The variabilities in the fabrication process will further improve the sensor uniqueness during prototype development.

REFERENCES

[1] K. Rosenfeld, G. Efstratios, K. Ramesh, "Sensor physical unclonable functions," *IEEE International Symposium on Hardware-Oriented Security and Trust (HOST)*, 2010, pp. 112-117.

[2] E. Bischur, S. Michel, N. Schwesinger, "Intentionally imperfectsensors for measuring mechanical parameters," in *Proc. International Conference on Sensing Technology (ICST)*, 2013, Dec 2013, pp. 597–602.

[3] H. Bleckmann, H. Schmitz, and G. Von der Emde, "Nature as a model for technical sensors," *Journal of Comparative Physiology A*, vol. 190(12), pp. 971-981, 2004.

[4] Z. Fan, J. Chen, J. Zou, J. Li, C. Liu, F. Delcomyn, "Development of artificial lateral-line flow sensors," *Proc. Solid-State Sensor, Actuator and Microsystems Workshop*, 2002, pp. 169-172.

[5] S. P. Mulvaney, P. E. Sheehan, "Nature Inspires Sensors To Do More with Less," *ACS Nano*, vol. 8, no. 10, pp. 9729-9732, 2014.

[6] Y. S. Lee, H. J. Lee, and E. Alasaarela, "Mutual authentication in wireless body sensor networks (WBSN) based on physical unclonable function (PUF)," in *Proc. 9th IEEE International Wireless Communications and Mobile Computing Conference (IWCMC)*, 2013 , pp. 1314-1318.

[7] B. K. Cyril and N. Schwesinger, "An improved capacitance-based intentionally imperfect sensor for measuring mechanical parameters," in *Proc. International Conference on Sensing Technology (ICST)*, 2014, pp. 230–235.

[8] E. Bischur, S. Michel, N. Schwesinger, "Intentionally imperfectsensors for measuring mechanical parameters," in *Proc. Sensing Technology(ICST), 2013 Seventh International Conference on*, Dec 2013, pp. 597–602.

[9] B. K Cyril and N. Schwesinger, "Design and fabrication of individualized capacitive microsensor for tilt measurement," *Accepted for IEEE Sensors 2015.*

[10] R. Maes and V. Ingrid, "Physically unclonable functions: A study on the state of the art and future research directions," *Towards Hardware-Intrinsic Security Springer Berlin Heidelberg*, 2010, pp. 3-37.

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