MODELING OF MULTIPLE ELECTRODE SYSTEM FOR INHOMOGENEITY DETECTION

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Abstract: Capacitive sensing gained on popularity through the last decades. From proximity sensors through humidity measurement to touch screen matrices. Capacitive sensing offers reliability, simplicity, and low financial cost. One of the crucial parts of the capacity sensor is the setup of the electrodes. The behavior of such setup is often needed to be known before application. Due to the complex nature of electrostatic arrays, the precise analytic solution is often unavailable so the other means to gain solution is needed. This paper focuses on using the simulation for modeling of multiple electrode setup, which could be used for measuring inhomogeneity in an otherwise homogeneous dielectric. The paper describes the problem of sharp edges. The description of the sensing depth of a planar capacitor is also included. Three simulations were created to prove initial assumptions.

Keywords: Ansys Electronics Desktop, capacitive sensing, Maxwell 2D and 3D, Model accuracy, planar capacitor, Simulation

1 INTRODUCTION

Capacitive sensing offers a wide range of solutions in almost every field of industry or science. It is often reliable, simple, and rather cheap. This paper focuses on an important capacity sensors principle, which uses fringe field detection and its usage for proximity detection. An inseparable part of every device is an analysis of its characteristics. Often the analytic solutions are sufficient, but sometimes the analytic solution can be non-existent. In these cases, simulations are the easiest way to provide the desired characterization.

This paper describes the problem of analytic solutions and modeling of a planar capacitor. Then explains the aspect of sensing depth, which is also demonstrated on two simple models, created in Ansys Maxwell 3D. After which the multielectrode set up is proposed, created, and analyzed. During the research, several problems emerged. All of those problems and their solutions are described.

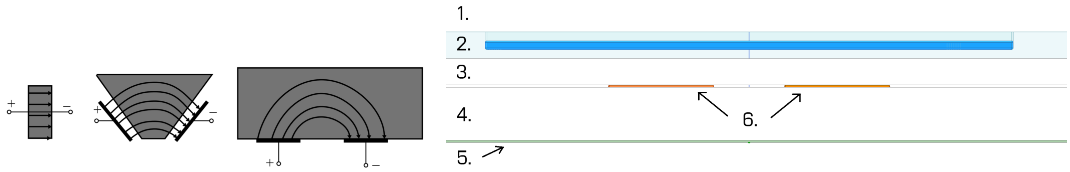
The main goal of this paper is not to design a perfect electrode setup, but rather to offer a reader an insight on what mistakes to avoid when creating a similar model.

2 PLANAR CAPACITOR

Capacitive sensing uses a wast variety of electrode setups. The best-known setup is a parallel plate capacitor, which contains two or three electrodes parallel to each other, with a dielectric in the middle. Capacity between two parallel electrodes is determined by a well-known equation 1. But this equation is valid only if the distance d is much smaller in comparison to area s. The larger the distance, the more noticeable the deviation from reality. The reason for deviations is the fringing effect at the end of the capacitor. The problem becomes much more complex if the electrodes are not parallel. If we open, figuratively speaking, the parallel capacitor, the equation stops to be even remotely valid and the planar capacitor is created.

$$C = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{s}{d} \; [F] \tag{1}$$

The planar capacitor uses two or more electrodes as well, but in this case, the plates are in the same plane. So the dielectric lies on the same side of the electrodes rather than in the middle of them. The difference between parallel and planar capacitors can be seen in the figure 1a.



(a) Planar capacitor [1]

(b) Side view of a model of a simple planar capacitor. 1. 3. and 4. polystyrene, 2. polystyrene layer with water, 5. shielding, 6. capacitor electrodes.

Figure 1: Transformation of a parallel plate capacitor into a planar capacitor and its model.

2.1 MODELING PLANAR CAPACITOR

There is currently no universal analytic solution for planar capacitors due to the complicated nature of electric fields.[2] However three methods exist to determine the analytic model for individual capacitive setups, but needless to say those methods often rely on simplification, such as infinite dimensions or ideal shape. As a result, such models are always an approximation of a real model. In addition, immense knowledge of a mathematics and physics apparatus is a necessity to derive such a model. Those methods are the method of images, the method of conformal mapping, and the solution of Laplace's equation. [3]

The more convenient and less demanding method, to determine expected behavior, is the use of simulation software with an application of the finite element methods (FEM). This method is numerical and therefore relies on the computational power of modern computers. The Ansys Maxwell implements this method and as such was used for the determination of capacity and sensing depth of the multiple electrode setup.

2.2 SENSING DEPTH

The planar capacitor can be described by several attributes, such as penetration depth, imaging resolution, signal strength, or measurement sensitivity. [4] This paper focuses on determining the penetration depth. The rest is a matter of future research.

The penetration depth can be described as the smallest detectable change of capacitance, for moving inhomogeneity away from the electrodes in an otherwise homogeneous dielectric.[1] Based on past research it seems that the sensing depth can be as much as half of a distance between the centroids of electrodes. But this concerns only the elementary shapes of electrodes, such as rectangle or ring. The effective depth is also dependent on the dimensions of electrodes. The penetration depth is demonstrated on two planar capacitor models with rectangular electrodes with different widths. Those models are described in section 3

3 SIMULATION OF A SIMPLE PLANAR CAPACITOR MODEL

For validation of the theory, the two iterations of the same model had been designed. The basis of the model consists of one planar capacitor with two electrodes, one shielding electrode, and polystyrene block with cut out for distilled water. The model can be seen in figure 1b. The materials were chosen, with future measurements in the mind. The polystyrene was chosen for its accessibility and water for its high permittivity. The width w of electrodes varies for both iterations. The first model has 2 cm wide electrodes, the second one 6 cm. The distance from its centroids is 10 cm for both models. The model was used for parametric simulation with parameter d [mm]. The range of parameter was $\langle 0;80\rangle$ with step of 5 mm. The parameter was bound to the distance of the water layer from the planar capacitor. The dimensions of polystyrene also changed accordingly. The total error was set to 0.05%. Each parametric simulation converged and satisfied the requirements. The shielding electrode was placed under the capacitor electrodes, to simulate shielding, which will be needed for real measurement.

From simulated data (figure 3a) it is observable, that the absolute capacity change (Δ_C) near the 50mm is rather small, only in the matter of fF. But in ideal conditions, this could be measurable. The capacitor with wider electrodes has, as expected, higher capacity, and the effective sensing depth is theoretically deeper by at least 5 cm.

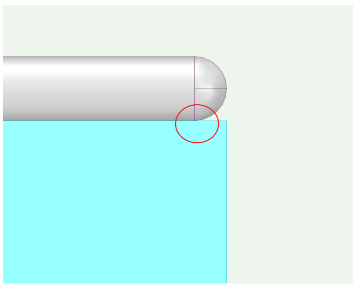
4 SIMULATION OF A MULTIPLE ELECTRODE MODEL

Another experiment was brought out to simulate more complex model with a multiple electrode setup. At its core, the model was almost identical to the previous one. However, 10 electrodes were placed into the model instead of two. The detail of the final electrode setup can be seen in figure 2b.

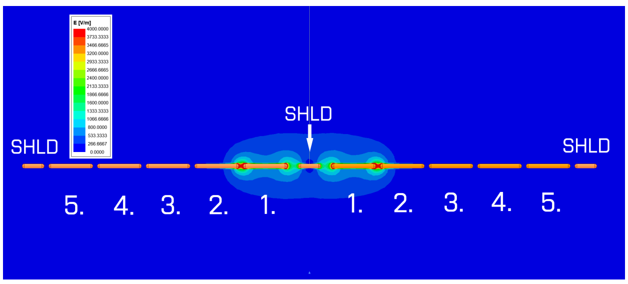
During the creation, many difficulties emerged. First of all, the convergence for this model was severely influenced by the sharp edges of the electrodes. Without filleting the edges, the simulation was unable to converge on an average PC, due to high computational requirements. It is known, that perfect edge creates a singular point that affects the simulated electric intensity E_i. The reason behind this is theoretically infinite E_i near the perfect edge. The finer the mesh the closer are the nodes to the edge, thus the simulation obtains higher intensity. This can be solved by filleting the edges or by bounding the convergence to the capacity, but with a cost of imprecision in E_i. The precise distribution of E_i was desired so the edges were rounded, which created another problem.

As can be seen in figure 2a, when the filleted electrode lays on top of the object, another sharp point is created. This time it does not affects the E_i, but the mesh has to be detailed, which inadvertently increases the computing demands. Also the performed simulation shows, that algorithm, generating the mesh, occasionally fails to create a valid mesh.

This problem was solved by hovering the electrodes above the objects. The distance between the electrodes was 0.2 mm from each side. The error created by this is negligible. Mainly because the expected accuracy of the sensing depth is in a range of a few mm.



(a) The creation of a miniature detail.



(b) Electric field around final multi-electrode setup, with inner electrode excitated.

Figure 2: The detail of a filleting problem and a side view of a multiple electrode planar capacitor

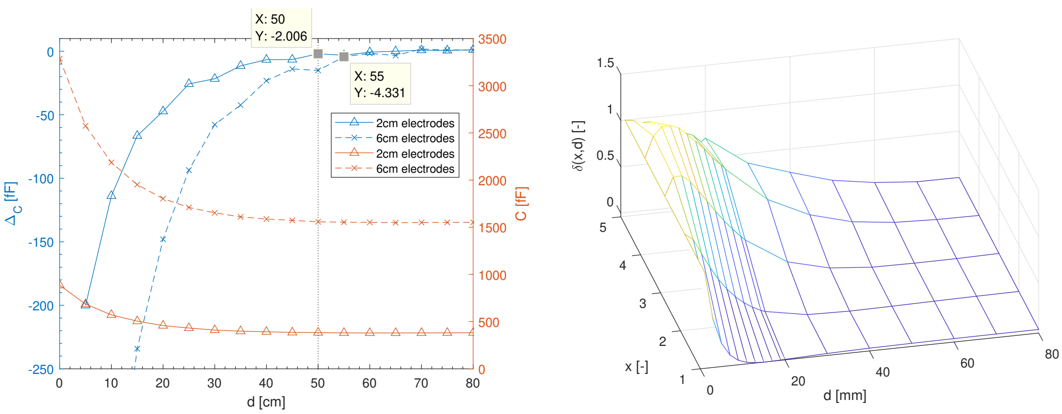
The measuring depth of the multi-electrode setup depends on combinations of excitated electrodes. Not only the opposing electrodes can be excitated. To strengthen the signal for deeper reach, more than just two electrodes can be used. This paper, however, shows only the excitation of the two opposing electrodes, with rest of the electrodes serving as a shield. So as of now, only five combinations were simulated. For every combination, the parametric simulation was performed. Other combinations are a matter of future research.

The presumption about distribution of capacitance was, that the capacitance will be largest for the middle electrodes and the smallest for outer electrodes.

The first iteration of model was similar to the final model, showed in figure 2b, but the Shields (SHLD) were not present. The shields were added because the first simulations showed, that the electrodes closest to the middle (1.) had unproportionally larger capacitance in comparison to other combinations. It was due to the significant contribution of the space between those electrodes. This problem was solved by inserting a shielding electrode between them. Subsequently, the simulation showed that the outer electrodes (5.) had higher capacitance than the ones situated beside them (4.), therefore failing the initial presumption about capacity distribution. The reason behind this was the fact that outer electrodes were shielded only from one side. This was solved by placing two other shielding electrodes on the outer rims. With this setup only the area on top and bottom of the planar capacitor is now influencing the final capacitance. The last iteration satisfies the initial presumption. The final distribution of capacity can be seen in table 1. The 1. in the table represents the combination of the electrodes closest to middle as seen in figure 2b.

Combination	1.	2.	3.	4.	5.
Capacity [fF]	-898.4808	-98.3735	-33.0574	-17.3396	-13.5462

Table 1: Distribution of capacity. The 1 being the electrodes closest to middle



(a) Capacity C and its increment Δ_C vs depth of inhomogeneity

(b) Dependence of $\delta(x,d)$ on excitation combination and distance of plywood layer.

Figure 3: Acquired dependencies.

5 DETECTING INHOMOGENITY

Early results show that by this setup, an inhomogeneity could be detected. By performing the following calculation of sensitivity $\delta(x,d)$.

$$\delta(x,d) = \frac{C(x,d) - C_0(x)}{C(x,d=0) - C_0(x)} \quad [-] \tag{2}$$

Where $C(x,d)$ is a capacity of electrode combination x in dependence on distance d of an inhomogeneity (water layer), $C_0(x)$ is a capacity with no inhomogeneity present and $C(x,d=0)$ is the highest capacity when $d=0$.

The result $\delta(x,d)$ is a standardized sensitivity value, which describes the reaction of an electrode setup to a distance of inhomogeneity in comparison to the capacity of a set up without inhomogeneity. The resulting function can be seen in figure 3b.

The results indicate, that the inhomogeneous layer could be detected. In the figure 3b it is noticeable, that the combinations of electrodes, that are furthest from each other (5.), react to larger depths of an inhomogeneity. Needless to say, that the capacity differences, in greater distances, are again a matter of fF, but by enlarging the electrodes, the capacity differences should also be more distinguishable.

Whats more interesting is, that by shielding excitated electrodes from both sides the sensitivity is not largest, when the inhomogeneity is nearest to the electrodes, but a bit further away. This phenomenon is best seen in figure 3b for excitation combination 4. This discovery could be essential for future research.

6 CONCLUSION

The principle and sensing depth of a planar capacitor sensing were described and demonstrated. Two models of planar capacitors were created, described, roughly evaluated, and used to confirm initial assumptions about the sensing depth. The results show, that the sensing depth could be as much as half of the distance between the centroids of the electrodes.

The model of multiple electrode planar capacitor was proposed, designed, and used in the simulation. During the creation, several problems occurred, but they were successfully solved. The important conclusion is to avoid the sharp edges when the precise distribution of E_i is required. The results of the simulation of multiple electrodes are promising. It seems that this setup could be used for future inhomogeneity detection, but it is a subject of future research. The comprehensive evaluation of multiple electrode model is planed. Also the verification by measurement is planned to determine the real effective sensing depth.

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