Design of Multi-channel Fringing Electric Field Sensors for Imaging – Part I: General Design Principles

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Abstract: **Multi-channel electric field sensors are used for electrical impedance and capacitance tomography applications. In cases where only one-sided access can be accommodated, fringing electric field sensors (FEF) sensors are used. The general design principles of multi-channel fringing electric field sensors are discussed in this paper. Analysis of the figures of merit of FEF sensors, such as penetration depth, signal strength, measurement sensitivity, and imaging resolution, are presented. The effects of design parameters on sensor performance are also evaluated. The qualitative design principles described in this part of the paper provide intuitive guidelines for the simulation-based design optimization procedure to be presented in the second part of the paper.**

INTRODUCTION

Multi-channel capacitive sensors are widely used for material property imaging. For such applications, the major goal of sensor design is to achieve high measurement sensitivity, high signal strength, and high imaging resolution and speed. Design parameters include electrode geometry, electrode and substrate material, number of electrodes, and positioning of guard electrodes.

The finite sensor head area makes it impossible to achieve all of the design goals simultaneously. Designing multi-channel sensors for imaging is, therefore, an iterative process of determining the optimal set of design parameters. The quantitative optimization process can be based either on analytical models [1] or on numerical simulations [2]. This paper focuses on the qualitative effect of design parameters on sensor performance. Evaluation of the qualitative effect aids the quantitative optimization process by providing intuitive design guidelines.

Among all of the design parameters, electrode geometry is the major determining factor for sensor performance. Sensors of various geometries were designed previously for imaging applications. For example, a multi-segment interdigital fringing electric field (FEF) sensor array was used for multi-phase interface detection in [3]; a multi-segment cylindrical sensor was used to image continuous flows of materials within a pipeline [4]; a helical wound electrode sensor and a concave electrode sensor were developed for void fraction measurements [5]. The choice of sensor geometry is usually dictated by the requirements of the application. In the cases where the sample can be accessed only from one side, FEF sensors can be used. Several such applications are being studied at the SEAL lab of the University of Washington. They include online measurement of moisture content in food products, pharmaceutical products, and paper pulp, as well as curing process monitoring of the resin transfer molding process.

This paper focuses on the design principles of multi-channel FEF sensors. The effects of electrode geometry on the performance of individual channels of interdigital FEF sensors is analyzed in [6], but it was not in the context of imaging applications, where imaging resolution and speed are of concern. However, some of the issues addressed in the present paper are not specific to FEF sensors, and the corresponding results can be applied to designing multi-channel imaging sensor of other types.

FIGURES OF MERIT

Penetration depth, measurement sensitivity, dynamic range, signal strength, and noise tolerance are the figures of merit usually used to evaluate the performance of multi-channel FEF sensors. For imaging applications, imaging resolution and speed of the sensor are also considered. The figures of merit of FEF sensors are analyzed in detail in the following sections.

Penetration depth

There is no consensus on the definition of penetration depth for FEF sensors. One way to evaluate effective penetration depth is to measure the position at which the difference between the current value and asymptotic (sample infinitely far from the sensor) value of sensor terminal impedance equals to 3% of the difference between the highest and the lowest values of the terminal impedance. The quantity is denoted as $\gamma_{3\%}$ [7]. Throughout this paper, this definition is adopted. Conceptually, it is an effective measure of how quickly the electrical field generated from the sensor decays as the distance from the plane of sensor electrode increases. Figure 1 provides an example where the penetration depth of an interdigital FEF sensor is evaluated using the above method. Capacitance values are normalized to the scale between 0 and 100%.

Penetration depth is determined mainly by the geometry of the sensor electrodes. For an interdigital sensor, penetration depth $\gamma_{3\%}$ is roughly proportional to its spatial wavelength λ.

Spatial wavelength is defined as the distance between the centerlines of neighboring fingers of the same type (e.g. driving or sensing electrodes). Figure 2 shows the cross-sectional view of an interdigital sensor. In Figure 2, the parameters l_1, l_2, and l_3 represent three different ways of connecting the electrodes. The letter "D" represents the driving electrodes, "S" represents the sensing electrodes and "G" represents the ground electrodes. In the table below the cross-sectional view of the sensor in Figure 2, each row corresponds to one of the three connection schemes; each column corresponds to the types of connection for the electrode directly above the column used in the different connection schemes. For l_1, an ac voltage signal is applied to every other electrode and the current/voltage at the un-driven electrode is measured. For l_2 and l_3, several un-driven fingers are chosen as ground electrodes and only the current/voltage at the sensing electrodes is measured. The ground electrodes are either connected to ground or kept at the same voltage potential as the sensing electrodes by using unity gain buffer amplifiers. The spatial wavelength of the sensor is increased ($\lambda_3 > \lambda_2 > \lambda_1$) by using different connection schemes. As a result, sensor penetration depth is also increased. The variable sensor penetration depth obtained from the different connection schemes provides the sensor with access to different layers of the test specimen.

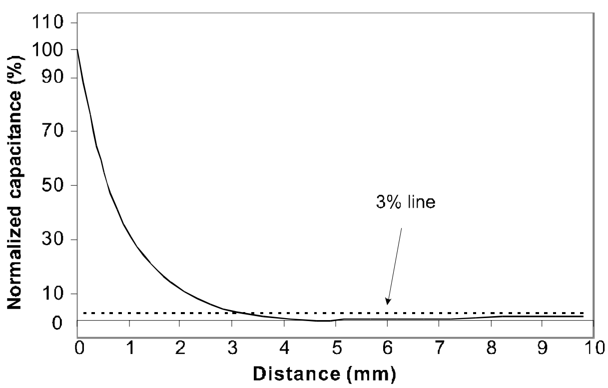

Figure 1. Evaluation of the effective penetration depth $\gamma_{3\%}$ of an FEF sensor.

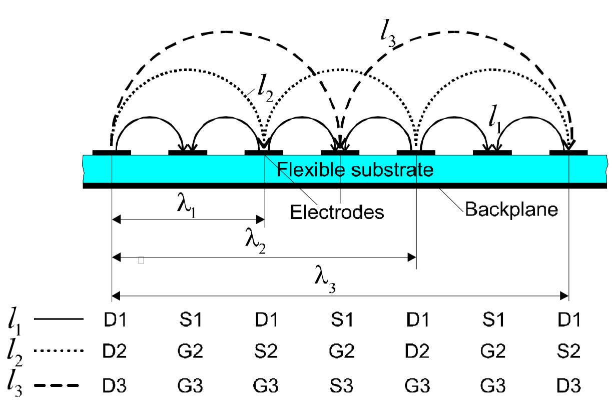

Figure 2. Cross-sectional view of a fringing electric field sensor with multiple penetration depth excitation patterns.

Measurement Sensitivity

Measurement sensitivity is defined as the slope of the sensor measurement curve, namely the ratio of the change in sensor output relative to the change in the measured physical parameter. The non-uniformity of the field distribution of FEF sensors makes their measurement sensitivities position-dependent. As illustrated in Figure 1, sensitivity decreases exponentially with increasing distance from the plane of sensor electrodes.

Electrode area is another major factor that determines measurement sensitivity. For a fixed spatial wavelength, greater electrode area means higher measurement sensitivity.

Dynamic Range

Sensor dynamic range is defined as the ratio between the largest and the smallest sensor output [8]. Its value is determined by the sample under test and should be within the measurement range of the interface circuit. The lower end of the circuit measurement range is determined by the sensitivity of the circuit, while the higher end is determined by factors such as the input common mode range of the operational amplifiers on the circuit.

Signal strength

The output signal for imaging applications is usually weak. The signal strength of FEF sensors decays exponentially with increasing distance to the sample. For non-contact measurements, the output signal is usually very weak. This requires that the interface circuit has high measurement resolution. To relax the requirement on the circuit, the distance between the sensor and the sample should be minimized. Signal strength can also be improved by increasing amplitude of the input driving signal. To avoid distortion, the sensor output has to lie within the measurement range of the interface circuit.

Noise tolerance

Guard electrodes are usually used to shield FEF sensors from noise disturbances. This includes both the guard ring on the top of the sensor substrate and the backplane under the sensor substrate. Proper positioning of these guard electrodes is crucial for design optimization. Special attention must be paid to the connection of the guard electrodes to avoid stray capacitances and ground loops. The driven-guard technique is always used to remove or reduce stray capacitances [9].

Imaging Resolution

A straightforward method to produce an image of material properties is to let each measurement channel of the sensor correspond to one pixel in the image. In this case, the larger the number of channels, the higher the imaging resolution. In tomography applications, where images are reconstructed from interpolations of the measurements from different channels, the number of pixels can be much greater than the measurement channels. Yet in this case, it is still desirable to have as many measurement channels as possible, because increased ratio of independent input channels to output pixels reduces the degree of ill-posedness inherent in image reconstruction. The finite sensor area dictates a tradeoff. For a sensor of fixed size, increasing the number of electrodes means decreasing the area of each electrode. This reduces the measurement sensitivity and signal strength of the sensor. If sensor output drops below the minimum signal level measurable by the interface circuit, the resulting measurement is inaccurate. The maximum number of electrodes is, therefore, limited by the measurement sensitivity of the interface circuit.

Imaging Speed

For real time measurement and control applications, the speed of imaging systems is of great concern. Imaging speed depends on the total number of measurement channels, the efficiency of the image reconstruction algorithm, and the frequency of the input driving signal. More channels means more data to be processed and longer image reconstruction time. The higher the input frequency, the faster the imaging speed. The upper limit of operating frequency is determined by the bandwidth of circuit elements (e.g. operational amplifiers) in the sensor interface circuit, as well as the bandwidth of the DAQ card when A/D conversion is performed directly on ac signals.

MAJOR DESIGN CONCERNS

Sensor electrode materials

Most sensor electrodes are made from metals. For example, a common practice is to fabricate sensors from PCB plates. Advancements in the field of conductive polymers brought about the alternative of plastic electrical sensors. Conductivity can be achieved in polymer composites by inserting electrically conductive particles into an insulating polymeric matrix. The doped polymers display metal-like behaviors including high electric thermal dependence and high conductivity. An extensive review of the state of art of conductive polymers is provided in [10]. Sensor electrodes made from conductive polymers are useful when optical information or mechanical flexibility is desired. For example, they were used to monitor the flow front position of the resin transfer molding process.

Surface contact quality

Due to the nonlinearity of its electric field distribution, FEF sensors are highly sensitive to the composition of the volume in the immediate vicinity around its electrodes. The smaller the wavelength of the sensor, the more pronounced is this phenomenon. For applications involving contact measurements of solid samples, surface contact quality is a major source of uncertainty. Non-ideal sensor-sample contact results in air gaps between the sample and the electrode surface. These air gaps act as a capacitance in series with the impedance of sample and lead to inaccurate measurements of material impedances if not accounted for.

Various methods are commonly used to improve sensor-sample contact quality. Products such as silver paints can be applied directly to the specimen as electrodes. They conform readily to the surfaces of samples and can greatly improve surface contact quality. The disadvantages of these electrodes are that they are usually difficult to pattern with high resolution and that they are difficult to remove afterwards, which makes them unfit for non-invasive measurements. In clinical applications of electrical impedance tomography, saline gels are utilized to improve electrode and skin contact quality.

For non-contact measurements, FEF sensors are much less sensitive to the surface roughness of electrodes and samples. For sensors of small wavelength (1-100 μm), it is important to keep the sensor surface clean, so that the contaminants between the electrodes do not dominate the sensor output.

Contact measurements and the Debye layer

In the case of contact measurements, when the sample under test has a finite conductance, a thin Debye layer (also called interfacial layer) forms at the interface between the sensor and the sample. The capacitance of this layer is usually much larger than the capacitance of the material and lies in series with the sample impedance to be measured. This large capacitance dominates at low frequency and may corrupt measurement accuracy if the system operating frequency is low. The Debye layer phenomenon can be avoided by using non-contact measurement or by adding a passivating layer on the sensor surface. It is worthy to note that the Debye layer itself provides useful information about the physical properties of the materials under test. The value of its capacitance can be estimated through electrochemical methods, the details of which are beyond the scope of this paper.

Sensor substrate and back plane geometry

The distribution of the sensor field energy is very sensitive to the geometry of the backplane (see Figure 2). Due to their close proximity to the driving electrodes on top of the substrate, the backplane draws significant amount of field energy away from the driving electrodes. This affects the sensor penetration depth and signal strength. Proper positioning and geometry design of backplanes are thus crucial to the optimization of sensor performance. The sensitivity of sensor output to backplanes can be controlled by the thickness of sensor substrate. In part II of this paper, the effect of substrate thickness on the output characteristics of FEF sensors is evaluated.

Cross talk between channels

The closer the channels are positioned together the stronger the crosstalk between the channels. It is therefore desirable to position the channels as far apart as possible. Other ways to reduce cross talk includes insertion of shielding electrodes between neighboring sensing pixels. Both of these methods lead to the reduction in the total surface area of active electrodes and loss in measurement sensitivity and signal strength.

Size limitation

For imaging applications, sensors electrode surface area is limited by the size of the sample to be imaged. The size limit of sensors leads to the interdependency of different output characteristics. In the design process, many trade-offs have to be made.

MAJOR DESIGN TRADE-OFFS

Penetration depth and measurement sensitivity vs. the number of channels

For an FEF sensor of a fixed size, to have more channels on the sensor, the sensor electrodes have to be placed closer to each other. This reduces the penetration depth and raises the level of cross talk. The measurement sensitivity is also harmed due to reduced electrode surface area for each channel. A secondary effect on measurement sensitivity is caused indirectly by the decrease in penetration depth: smaller penetration depth makes the field energy much more concentrated around the sensor electrodes, thus makes the sensor output less sensitive to variations in the sample. These trade-offs limit the number of channels that a FEF sensor can have.

Imaging resolution vs. measurement sensitivity and imaging speed

Using a larger number of smaller electrodes improves imaging resolution but this has two disadvantages. Increased number of measurement channels reduces imaging speed and smaller size of electrodes reduces measurement sensitivity. The loss in speed and sensitivity can be compensated by, respectively, higher measurement sensitivity of the interface circuit and higher system operating frequency. High operating frequency requires, in turn, for the interface circuit to have a sufficient bandwidth. Examples of circuits with high sensitivity and bandwidth are provided in [11,12].

CONCLUSIONS

This paper presented a tutorial compilation of principles for design of multi-channel FEF sensors. Special focus is placed on the analysis of figures of merit and the major trade-offs caused by various design constraints. The effect of design parameters on sensor performance is also analyzed. These qualitative guidelines are useful to understand the logic behind the simulation-based design procedures described in the Part II of this paper.

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