Holistic analysis for electrical capacitance tomography front-end electronics

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Abstract. The design and realization of capacitive measurement systems requires a variety of prior knowledge of the system, to achieve the intended performance. Electrical capacitance tomography (ECT) is a high-end application of capacitive sensing. The required electronics is usually tailored to specific application constraints. To compare suitable circuit structures, a holistic design framework is required considering all components and their mutual interactions to derive appropriate figures of merit. We present an analysis framework and exemplary compare two different ECT circuit structures with respect to their sensitivity. The framework incorporates real world sensor conditions, for the application of the system.

1. Introduction
Capacitive measurement principles are well established to gain knowledge about a physical quantity of interest [1]. The fundamental principle of capacitive sensing is based on a variation of a measurement capacitance [1]. A high-end application for tomographic imaging of spatial dielectric material properties, is Electrical Capacitance Tomography (ECT). It is an inverse measurement problem based on capacitive measurements between multiple electrodes. A main application of ECT is process monitoring. Fig. 1 shows a typical ECT system, including a sensor which encloses the Region Of Interest (ROI). The sensor electrodes are attached to individual front-ends (FE). Each front-end can be operated in excitation- (TX) or receive- (RX) mode. Dedicated analog signal conditioning structures are usually needed for ECT systems. The receiver structure is mainly realized by a low impedance displacement current measurement circuit [2], which is implemented by means of a transimpedance amplifier [3]-[6]. The signal is than post processed by an additional amplification stage. Various authors have suggested different realizations of this amplifier structure. E.g. a fixed gain stage [3], a variable/programmable gain amplifier [4] or a logarithmic amplifier [5],[6] are suggested.

To analyze and compare different ECT circuits, a holistic framework is required which incorporates all system components and enables a comprehensive evaluation of important system properties e.g. sensitivity and noise performance. In this paper we present a holistic modeling approach, and demonstrate a comparative sensitivity analysis of two possible ECT system realizations. We aim on the application of an ECT system for flow imaging in pneumatic conveying processes of pulverized materials with a low relative permittivity \(\varepsilon_r\) [7]. Fig. 2a depicts the different flow profiles for pneumatic conveying. To incorporate the flow process in the analysis framework, we draw a large number of random samples for all the different flow profiles.
Figure 1: ECT system consisting of eight (gray) electrodes and front-ends FE_i, arranged around a non-conductive pipe (black circle) [2]. The sensor is surrounded by a screen (dash-dotted circle), which is connected to system ground.

(a) Categorization of different flow schemes in pneumatic conveying, as a function of pressure drop over the gas velocity [7].

Figure 2: Incorporation of the flow profile for the evaluation: Samples (b) are generated for the different flow regimes. All capacitances within the sensor are simulated and incorporated into the framework.

2. System modeling for two different structures

Fig. 3 shows two different ECT circuit structures which are modeled by the holistic framework for comparison. Each system consists of a sinusoidal excitation source with amplitude \( V_{TX} \), source impedance \( Z_{out} \) and frequency \( f_{TX} \). The second system block from the left, represents an eight electrode ECT sensor. The sensor is followed by a transimpedance amplifier with input impedance \( Z_{in} \) and gain factor \( G_{IV} \). The fourth system block from the left, shows two different amplification stages with gain \( G_{log} \) and \( G_{lin} \) for Fig. 3a and Fig. 3b, respectively. A low pass filter with attenuation \( A_{LPF,i} \) and cut-off frequency \( f_{c,LPF,i} \) is used to limit the measurement signal bandwidth. The received measurement signal is sampled by an analog to digital converter with full scale range \( FSR_i \) and sample frequency \( f_{s,i} \).

Figure 3: Analyzed measurement systems consisting, from left to the right, of an excitation source, an ECT sensor, a current to voltage converter, an amplification stage, a low pass filter and an analog to digital converter. The amplification block in the upper system is realized by a logarithmic amplifier. The linear system in the lower sketch uses a variable gain amplifier VGA, which is controlled by a control voltage \( V_{ctrl} \).
The system shown in Fig. 3a uses a logarithmic amplifier with integrated Root Mean Square (RMS) detector, as additional gain stage. The logarithmic amplifier converts the sinusoidal input voltage $V_{\text{in, log}}$ into a voltage, proportional to the logarithm of its RMS value. We refer to the output voltage $V_{\text{out, log}}$ as RMS voltage. Systems making use of a logarithmic amplifier have been suggested because of a high dynamic range [6]. However the logarithmic amplifier causes a non linear system behaviour.

The gain stage of the system depicted in Fig. 3b uses a variable gain amplifier VGA. The VGA gain setting is controlled by $V_{\text{ctrl}}$. This control voltage can be freely adjusted e.g. by means of a superordinate control strategy.

3. System comparison
In this section a sensitivity analysis of the two measurement systems depicted in Fig. 3 is shown. To allow a fair comparison, both systems are using the same excitation source, transimpedance amplifier and sensor structure. As logarithmic amplifier the AD8306 from Analog Devices is used, which converts an alternating input voltage $V_{\text{in, log}}$ into an RMS output voltage $V_{\text{out, log}}$ following the relation

$$V_{\text{out, log}} = V_Y \cdot 20 \cdot \log_{10} \left( \frac{V_{\text{in, log}}}{V_X} \right).$$  \hspace{1cm} (1)

$V_Y$ refers to the slope voltage and $V_X$ to the intercept voltage [9]. To investigate the sensitivity of the logarithmic amplifier based receiver structure shown in Fig. 3a, an adjacent electrode pair (e.g. from FE$_{2}$ to FE$_{3}$ in Fig. 1), as well as a distant electrode pair (e.g. from FE$_{2}$ to FE$_{6}$) are analyzed. The dashed trend in Fig. 4 shows the amplifier RMS output voltage $V_{\text{out, log}}$, as function of the input voltage $V_{\text{in, log}}$, following equation (1). The two blue histograms (their corresponding ordinate is at the right side of Fig. 4) show the input voltage distributions. The resulting RMS output voltage histograms and their abscissa are marked red. The high input voltage for an adjacent electrode pair leads to an RMS output voltage $V_{\text{out, log}}$ close to the upper output range of the AD8306. In this range the dashed voltage conversion trend, expressed by equation (1), has a small slope. The slope has a direct impact on the (red) distribution of the logarithmic amplifier output voltage $V_{\text{out, log}}$, by means of its width. A compression effect occurs for the adjacent electrode pair, resulting in a narrow output RMS voltage distribution. For a distant electrode pair, the voltage conversion has a larger slope and results in a wider RMS output distribution, which leads to a higher sensitivity. To compare the logarithmic structure in Fig. 3a with the linear one in Fig. 3b, the distant electrode pair is used.

Fig. 5 shows the resulting RMS output voltage distributions for a distant electrode pair, for both systems in Fig. 3. To allow a meaningful comparison, both trends are digitized by a 16 Bit analoge to digital converter with the same full scale range $FSR_i$. As the linear structure in Fig. 3b evaluates a sine wave, the digitized result is expressed by its Root Mean Square (RMS) value. As can be seen, the linear structure provides a wider distribution, than the logarithmic one. Therefore a higher sensitivity can be achieved by the use of a linear amplifier. The use of a variable gain amplifier also allows direct control of its gain, and thus the width of the distribution. The logarithmic amplifier’s gain, and thus the output distribution is a function of the input signal’s magnitude, and allows no direct control of the gain setting.

The influence of the VGA gain on its output distribution can be seen in Fig. 6. It should be mentioned that a bipolar analoge to digital converter is required for the linear approach in Fig. 3b, to sample the positive and negative sinusoidal half-wave. For each half-wave, the half full scale range of the ADC is used. By observing the RMS value of the digitized distribution, the maximum output code is given by $\frac{FSR_{\text{lin}}}{2\sqrt{2}}$, and is marked in Fig. 6.
4. Conclusion

In this paper we presented a holistic framework for analysis of electrical capacitance tomography front-end electronics. The flow process is incorporated by means of samples to evaluate all capacitances within the sensor. This capacitances are used to compare the signal integrity of two suitable receiver structures. We demonstrated the application by means of a comparative sensitivity analysis for a system with a linear amplifier and a logarithmic amplifier. We demonstrated a better sensitivity for the linear system with respect to the logarithmic amplifier approach for the analyzed transport process. The holistic analysis framework can be further extended for different analysis types e.g. noise, to allow for a fair comparison between systems.

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