# A digital signal processing algorithm on read out circuit for electrical capacitance tomography

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# A Digital Signal Processing Algorithm on Read Out Circuit for Electrical Capacitance Tomography

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***Abstract*—The research relates to tomography technique based on electrical mass properties measurement. This study proposed electronic design of read out circuit (ROC) for signal processing in electrical capacitance tomography. The method is to capture the excitation and detection signal simultaneously using high speed analog-to-digital-converter (ADC) then save its reading to first-in-first-out (FIFO) memory. From the two signals, magnitude and phase can be determined. Therefore, calculation of capacitance and conductivity of object inside sensor is done using math equation.

***Keywords—electrical capacitance tomography, read out circuit, high speed ADC, signal processing, zero derivative method.***

## I. Introduction

Tomography is two or three dimensional image visualization technique based on signal measurement from the sensor. There are several kinds of tomography technique, viz. acoustic tomography, radiation tomography, and electrical tomography [1]. Acoustic tomography is based on sound wave measurement; whereas radiation tomography is based on radiation wave measurement; and electrical tomography is based on electrical mass properties measurement. The principle of electrical capacitance tomography (Figure 1) is injection of square wave or sine wave signal into electrode, which will cause fringing electric field inside sensor area. Then, the signal is detected by detector to be further processed and reconstructed into image using soft computing algorithm.

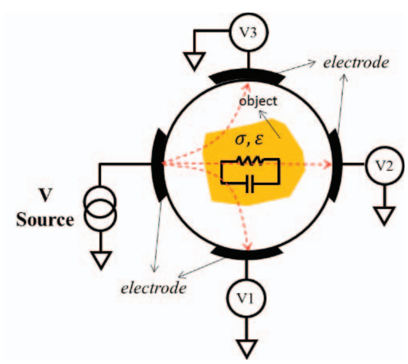


Figure 1. Principle of electrical capacitance tomography (ECT)

Previous design [2,3] use an analog circuit that has many associated problems such as noise, component mis-match on amplifier, and controlling input offset and gain. Digital signal processing is needed to overcome the shortcoming of existing analog circuit. This research introduces an electronics design namely read out circuit (ROC) to process signal based on high speed analog-to-digital converter (ADC) and FIFO memory. The method is to capture the excitation and detection signal simultaneously using high speed ADC then save its reading to first-in-first-out (FIFO) memory. From the two signals, magnitude and phase can determined. Therefore, calculation of capacitance and impedance of object inside sensor is done using math equation. With this method, the system can be used not only to measure capacitance, but also to measure conductivity of the object.

## II. Digital Signal Processing Method

### *A. Theory of Operation*

An electrical capacitance tomography (ECT) uses a sine wave signal for excitation electrode, while detection electrode also measures a sine wave signal which contains amplitude, frequency, and phase information. It is assumed that the excitation signal is $V_i sin(\omega t)$ and detection signal is $V_o sin(\omega t)$ that has period $(dt_1)$ and the *t* difference is $(dt_2)$ as shown in Figure 2.

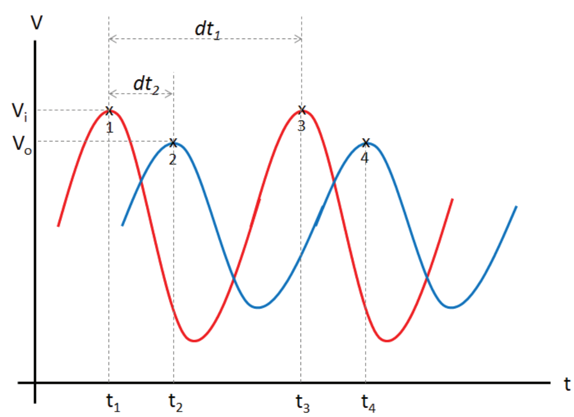


Figure 2. Method to calculate magnitude, frequency, and signalphase

The method to process the signal is to capture detection signal *($V_o$)* and excitation signal *($V_i$)* simultaneously to determine magnitude, frequency, and phase of the signal. It should be done first by identifying location "*t*" of the peak of both of signals, hence obtaining $t_1$, $t_2$, $t_3$ and $t_4$. From the excitation signal, period and frequency can be calculated. Moreover from both of signals (excitation and detection), angle can be calculated. The equation is expressed as:

$$f = \frac{1}{d_{t1} t_s};\ d_{t1} = t_3 - t_1 \tag{1}$$

$$\theta = \frac{d_{t2}}{d_{t1}} 360;\ d_{t2} = t_2 - t_1 \tag{2}$$

where $f$ is frequency output, $t_s$ is time sampling of ADC, $d_{t1}$ is the difference between $t_3$ and $t_1$, $d_{t2}$ is the difference between $t_2$ and $t_1$, $\theta$ is the angle of the signal. The impedance ($Z_x$) can be calculated from excitation voltage ($V_i$) divided by detection voltage *($V_o$)* and multiplied by the impedance of feedback components on the OpAmp $(R_f//C_f)$, as shown in following equation:

$$Z_x = \frac{V_i}{V_o} Z_f \tag{3}$$

The impedance of feedback components can be calculated as:

$$Z_f = \frac{R_f X_c}{R_f + X_c};\ X_c = \frac{1}{\omega C_f} \tag{4}$$

Where, $R_f$ is feedback resistance, $X_c$ is reactance of feedback capacitance, $C_f$ is capacitance feedback, and $\omega$ is angular frequency of the signal.

The impedance $Z_x$ contains resistance (real value $R_{ESR}$) and reactance (imaginary value $jX$) where it can be written as:

$$Z_x = R_{ESR} + jX \tag{5}$$

The imaginary value can be of capacitance or inductance depend on electrode and object material inside the sensor. In this work only capacitance and impedance of the capacitance sensor is measured, thus the equation (5) can be rewritten as equation (6), and also rewritten as equation (7) if consisting sinusoidal signal.

$$Z_x = R_{ESR} - \frac{j}{\omega C} \tag{6}$$

$$Z_x = Z_x \cos\theta + jZ_x \sin\theta \tag{7}$$

From the equation (7) real and imaginary value can be found and expressed as:

$$R_{ESR} = Z_x \cos\theta \tag{8}$$

$$C_x = \frac{-1}{\omega Z_x \sin\theta} \tag{9}$$

Where, $Z_x$ is impedance of the object, $R_{ESR}$ is resistance of the object, $C_x$ is capacitance of the object, measured inside sensor.

The signal from detection electrode is too small and difficult to analyze so that the electronic circuit such as charge amplifier circuit as depicted in Figure 3 is needed. The charge amplifier circuit has a function to convert the current from detection electrode into voltage signal. $V_i(t)$ and $V_o(t)$ are sine wave signal input and output respectively, $Z_x$ is object impedance will be measured, $R_f$ and $C_f$ are resistance and capacitance feedback, $Z_{s1}$ and $Z_{s2}$ are parasitic impedance from coaxial cable, and sensor screen.

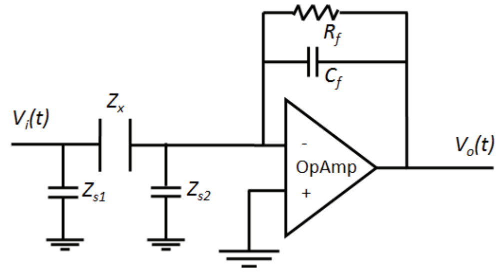


Figure 3. Charge amplifier circuit

## B. Digital Peak Detection

Signal from charge amplifier circuit is in sine wave form. To make the signal further processable, magnitude value of signal voltage must be captured. There are two methods for magnitude detection; first, using analog peak detection which produce DC (direct current) voltage value. Second, using digital peak detection as described in this work.

Magnitude detection in the digital signal processing is very important, it is used to find the position of $t_1$, $t_2$, $t_3$ and $t_4$, so that the frequency and phase signal can be calculated. The method of digital peak detection in this work is zero-derivative method, viz. measures the slope of the function at a single point using first derivative. First derivative is commonly used to identify the slope at a particular point is negative, positive, or zero of the nonlinear function as depicted in Figure 4.

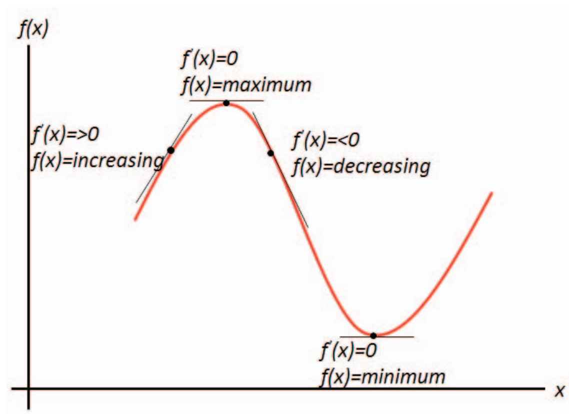


Figure 4. First derivative to detect slope at particular point

The signal excitation and detection in the electrical capacitance tomography system is sine wave as $f(x) = \sin x$. The maximum and minimum value occurs at the point at which the first derivative is zero. The first derivative of sine wave function can be expressed as:

$$f(x) = \sin x \tag{10}$$

$$f'(x) = \cos x \tag{11}$$

Based on the first derivative, the max and min value of the signal occurs at every $0.5\pi$, $1.5\pi$, $2.5\pi$, $3.5\pi$, etc. Signal on digital signal processing is discrete value and dependant on sampling time of the ADC, so that the equation (11) can be expressed as:

$$f'(x_i) = \cos\left(x_i \frac{f_{in}}{f_s} 360\right) \qquad (12)$$

Where $x_i$ is number of data, $f_{in}$ is frequency input, $f_s$ is frequency sampling of ADC. The equation (12) could be used in one condition, viz. the first value of the function must be zero or close to zero: $f(x_0) \cong 0$. Consequently, the trigger is necessary to be arranged close to zero to obtain the first data equal or close to zero.

## III. READ OUT CIRCUIT DESIGN

Read out circuit (ROC) has a function to capture the signal from electrode sensor and process it into capacitance and impedance. Read out circuit use two high speed analog-to-digital conversion (ADC), two memories FIFO (first-in- first-out), and one microcontroller as shown in Figure 5. High speed ADC is used to capture both signals simultaneously with sampling rate of 20 MSPS (mega samples per second). The microcontroller cannot fetch data from ADC directly, because the input output (I/O) port only 1.5 Mbps of speed. Hence, another device to bridge ADC and microcontroller such as FIFO memory is required. Memory FIFO is used as temporary buffer, to save the digital data from ADC with the same clock of ADC and FIFO. In this work, a microcontroller being used is atxmega 16-bit bus with clock speed of 32MHz, which has a function to analyze and process the signal into capacitance and impedance.

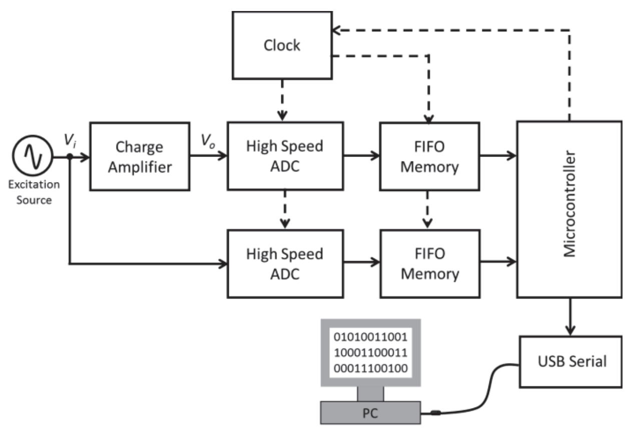


Figure 5. Circuit diagram of read out circuit

There are several factors that should be considered in developing read out circuit, which will be guarantee good linearity and sensitivity. Some factors such as the chosen of electronics parameters, frequency, and amplitude of signal excitation. The capacitance and resistance feedback cannot be too large to offer shorter settling time [4]. A higher excitation frequency is proportional to higher sensitivity, faster data collection rates, and also reducing the effect of conductivity of the object measured inside sensor [5]. A higher amplitude of excitation signal is also rising the signal-to-noise-ratio (SNR) [6].

Based on consideration of several above factors, the feedback resistance and capacitance are 22KΩ and 22pF respectively, the frequency excitation is 500KHz, and the amplitude signal excitation is 21.6 Vp-p. The system performance is also determined by characteristic of ADC. In this work, a 12-bit, sampling rate up to 53 MSPS of ADC chip ads807, which has an input range of 3 Vp-p and SNR of 67.5 dB is used. Subsequently, these parameters will be obtained: the settling time of the charge amplifier circuit is 3.7 µs, the sensitivity is 0.38 $VpF^{-1}$, the upper limit of capacitance measurement is 3 pF, and the upper limit of conductivity measurement is 15.9 $\mu Sm^{-1}$.

A capacitance sensor is used to examine and verify the signal-processing algorithm on the read out circuit design. It could measure capacitance and conductivity of the object inside sensor at the same time.

## IV. EXPERIMENTAL RESULTS

The experiment was conducted with a 8 channel circular sensor with 13.5 cm diameter and 4.5x7.2 cm of electrode dimension, whose cross-sectional diagram is shown in Figure 6. The electrodes in the sensor can act as excitation or detection source depend on which one the electrode pair was activated. Capacitance reading retreived from electrode pairs $C_{1-2}$, $C_{1-3}$,…, $C_{1-8}$, $C_{2-3}$, $C_{2-4}$,…,$C_{2-8}$, $C_{3-4}$, $C_{3-5}$,…$C_{3-8}$, so on until $C_{7-8}$. In general, $N$ electrode sensor offers $N(N-1)/2$ independent capacitance data measurement. Hence, the number of independent capacitance measurement for eight electrodes is 28 data. To getting all data measurement, each electrode pair measured one by one manually until the last measurement data.

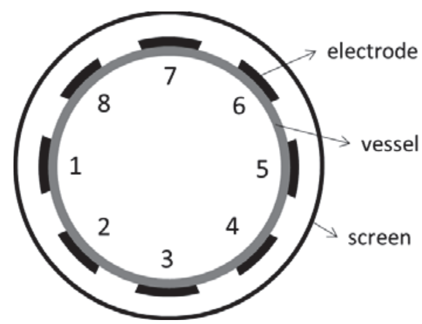


Figure 6. Cross-sectional of 8 channel capacitance sensor

A photograph of prototype of read out circuit (ROC), eight channel capacitance sensor, and several phantom are shown in Figure 7. To investigate the result, specific phantom has been made from pvc with diameter 2.5 cm and 6 cm, and also square phantom with dimension 4.2x8 cm. Phantom was filled up with solid salt (εr=15).

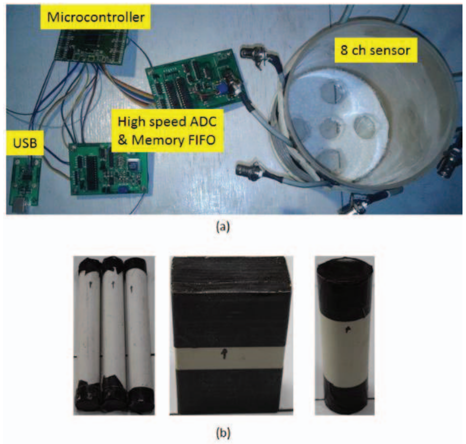

Figure 7. Photograph of (a) Read Out Circuit (ROC) and sensor Prototype; (b) Phantom used in experiment

In the following experiment is used a direct digital synthesizer (DDS) that has function to generate the excitation signal set to 500 KHz, 21.6 Vpp. Meanwhile, the ADC sampling rate is set to 20MSPS (50 ns of time sampling), thus resulting 40 digital data for a signal cycle. Each signal processing involves 200 sampling points (5 signal cycle) to guarantee desirable measurement. The fetching data from memory FIFO to microcontroller is about 1 µs each data bits, thus it takes 200 µs for all sampling point. The processing signal including conversion digital data into voltage, digital signal filtering, digital peak detection, and calculation phase, capacitance, impedance, and conductivity will takes about 95.8 ms. In this way, it will takes 96 ms to measure one capacitance impedance, and conductivity. With such amount of time, it is too slow if implemented in ECT data acquisition system. However it is currently not a concern of the work. This work focuses on digital signal processing implemented on read out circuit (ROC) for ECT system. The speed of measurement data could be increased by replacing the microcontroller with high speed digital signal processor (DSP), using field programmable gate array (FPGA), or using complex programmable logic device (CPLD) being used by other researchers [7-9].

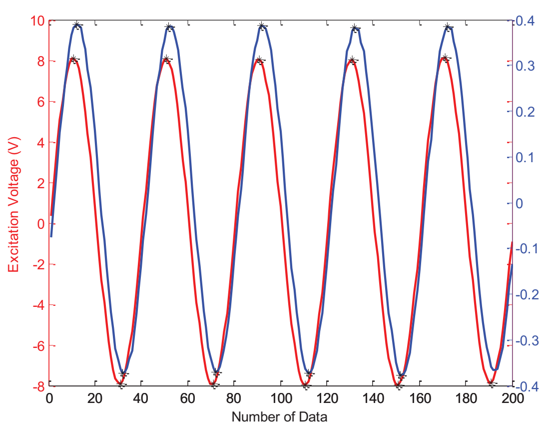

Figure 8. Result of digital peak detection

The signal was interfered by some noise from environment, thus the digital signal filtering is needed to make signal smooth and easy to process. As an example is digital peak detection, which requires a signal free from noise. The result is shown in Figure 8.

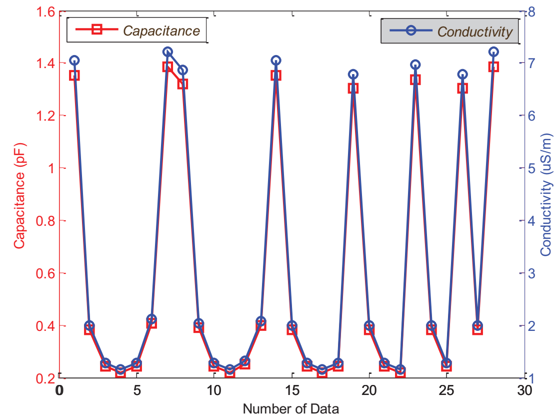

Figure 9. Capacitance and conductivity measurement for 8 electrode sensor

To validate the read out circuit system, image reconstruction is carried out. For image reconstruction, capacitance measurement is normalized using equation:

$$nc = \frac{C_r - C_l}{C_l} \tag{13}$$

Where $nc$ is normalized capacitance, $C_r$ is measured capacitance, $C_l$ is capacitance at empty calibration. Empty calibration is when the sensor filled with low permittivity material, which is dry rice (εr=3.5). Iterative Linear Back Projection (ILBP) algorithm was used to reconstruct all data patterns, and not discussed in this paper. Thorough explanation about algorithm's implementation can be found in [10]. Capacitance and conductivity measurement of the 8-electrode sensor are described in Figure 9. Adjacent pair electrode give capacitance and conductivity measurement up to 1.39 pF and 7.2 $\mu Sm^{-1}$ respectively; while opposite pair electrode give capacitance and conductivity measurement of 0.22 pF and 1.1 $\mu Sm^{-1}$ respectively.

The image reconstruction from several phantoms are shown in Figure 10, which is divided into four experiment. The circle rod with diameter of 6 cm yields a good reconstructed image. On the contrary, image reconstruction of square rod with dimension of 4.2x8 cm is not good enough. The left and the right sides attracted to the edge of the sensor, so that the image looks a little bloated. In the last experiment, the circle rod with diameter of 2.5 cm yields good image reconstruction even though there is some noise in the edge of the sensor.

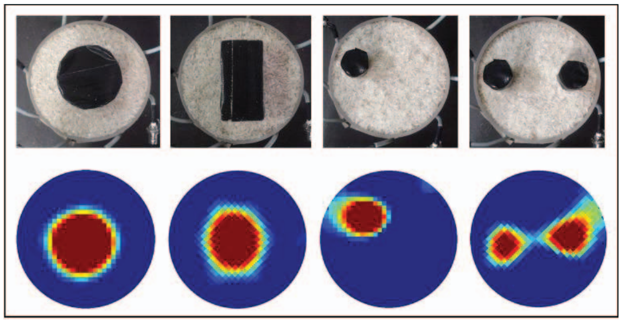

Figure 10. Image reconstruction for several phantom

## V. Conclusion

The prototype of read out circuit (ROC) for signal processing based on high speed ADC and memory FIFO for electrical capacitance tomography has been assembled. The ROC can be used not only to measure capacitance, but also to measure conductivity of object inside sensor. The measurement sensitivity is 0.38 $VpF^{-1}$, the upper limit of capacitance measurement is 3 pF, and the upper limit of conductivity measurement is 15.9 $\mu Sm^{-1}$. The speed of digital signal processing that use microcontroller is too slow, it will takes 96 ms for one measurement. The speed could be increased by replacing the microcontroller using DSP, FPGA, or CPLD. Experimental result shows that image reconstruction was good enough so that the pattern is observable, although still with some obscurities.

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