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Circuit and Signal Processing for Capacitance Measurement of Breast Tissue

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In previous studies, electrical capacitance tomography has been developed and applied for imaging breast tissue to detect abnormalities within the breast caused by simple cysts, benign tumors and malignant cancers. For accurate screening and early detection of such abnormalities, high sensitive capacitance sensor is necessary. This study proposes a novel capacitance sensor circuit and signal conditioning and processing based on capacitance–voltage circuit for breast tissue measurement. The new sensor circuit design used a biopotential capacitance electrode, capable of measuring capacitance value with a resolution as low as 0.1 fF, a sensitivity of 1.6 V/pF, and linearity of 0.98. The experiment was conducted with a hemisphere 3D sensor 24 electrodes. The experiment strategy is as follow, first the system will be calibrated using network analyzer, secondly experiment using phantom 1, and the third experiment using phantom 2. In the design, we used a reference electrode made from fixed plate to measure capacitance inside the system, which will be used further for compensation against signal fluctuation caused by environmental condition such as humidity, temperature, pressure, etc. As a result, more stable system is achieved. Based on the experiment, the system can detect abnormalities of the human breast which are represented by two phantoms with different condition.

Keywords: Capacitance Measurement, Signal Processing, Sensitivity, Breast Tissue, Cancer Detection, Biopotential Electrodes.

1. INTRODUCTION

Early detection of breast cancers and other abnormalities within the breast is extremely of importance to get effective therapy and avoid fatalities. A number of techniques used widely to detect lump within the breast in medical practices are Ultrasonography (USG) and Mammography as these methods relatively cheap and easy to use as compared to Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) scan. The limitation of these conventional methods for early detection of abnormalities within the breast is, that in many cases, a tingling sensation or a present of lumps felt by a patient is not always confirmed by USG or Mammography until the lump became big enough, which is often already too late. Lumps with sizes under 1 cm in diameter within the breast usually are difficult to detect. Alternative methods which are fast, simple to use, high safety, non-radiation and low cost are still in needs to develop.

Microwave tomographic imaging introduces significant capability as a new method for breast cancer early detection based on contrasts between dielectric properties of healthy versus malignant tissues.[1] However, its broadband natures make the implementation expensive and complex in hardware levels. Recently, electrical impedance spectroscopy as a mean of non-invasive medical technique that performs surface electrical measurement was investigated for breast imaging. The system utilizes simple microcontroller-based circuitry to sense the electrical property changes in the body to alternating current. The technique was claimed as a complementary to mammography and magnetic resonance imaging (MRI) for breast cancer detection.[2] Electrical tomography is considered as having

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high sensitivity of electrical properties measurement of breast tissue so that design methods of circuit and system have been sought continuously.[3]

In our previous published studies, we have developed the first usage of electrical capacitance volume tomography (ECVT) for breast cancer imaging called ECVT Breast Imaging.[4] The technique is based on capacitance measurement of the breast tissue using a number of capacitive sensors arranged surrounding outside of the breast and image reconstruction using tomography algorithm of the breast tissue from the measured capacitance data. The technique is very fast, i.e., less than one second to get the whole volumetric image of the breast with abnormalities inside, non-radiation and low-cost. However, the data acquisition of the capacitance measurement used in the imaging system is sometimes prone to stray capacitance that often caused artifacts in the reconstructed image, and hence false diagnosis. To perform very early and highly accurate detection of abnormalities, a stray immune and high sensitive capacitance sensing is needed to be developed.

Our previous data acquisition system used for breast imaging has major constrains in the sensitivity and resolution which are only 0.56 V/pF and 0.42 fF, respectively. Thus, it is still on demand to improve. In this study, we develop electronic circuit and signal processing for more accurate and higher sensitive capacitance measurement of breast tissues. To improve the sensitivity and stability, a simultaneous ADC and reference electrode are used.

2. SENSING AND SIGNAL CONDITIONING CIRCUIT

Sensing and signal conditioning circuits are used to convert capacitance signal from electrode to DC signal for further process. The circuit is consisting of signal generator, capacitance-to-voltage (C–V) circuit, and DC restoration circuit.[6,10]

2.1. Biopotential Electrodes

The most important consideration to be made for the sensing of electric signal from human body is biopotential electrode with some requirements such as safety from electric discharge and high input impedance.[7,8] Figure 1(a) represents a biopotential electrode which consists of electrode and dielectric. The electrical characteristics of biopotential electrode generally is nonlinear, therefore performed a linear approach in its application. In ideal condition, electrodes can be represented by an equivalent circuit as shown in Figure 1(b) where, E_{hc} is half-cell potential, Rd and Cd are components that represent impedances associated with electrode-dielectric interface and polarization at the interface. R_s is series resistance associated with resistance material of the electrode.

The electrode design in this research is fashioned to measure capacitance inside the breast tissue as a high

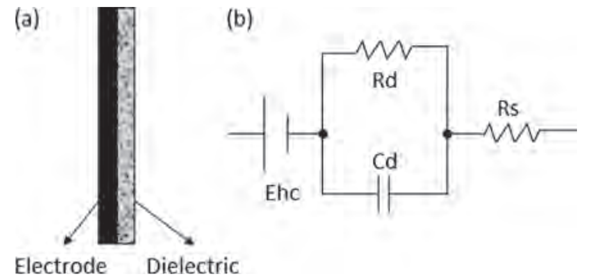


Figure 1. (a) Biopotential electrode; (b) equivalent circuit for biopotential electrode.

dielectric material used in the capacitive bioelectrode to form a capacitor between the skin and the electrode. Figure 2 shows the block diagram to sense capacitance of breast tissue. Breast is surrounded by several bioelectrodes and connected to electronic circuit and personal computer (PC). Electronic circuit contains signal generator and signal processing unit. Signal generator produces sine-wave signal injected into the bioelectrode as excitation electrode, while signal processing is converts the capacitance signal from detection electrode into voltage for further process. The electric field will be generated between electrodes pair inside breast, thus the unknown capacitance (C_x) inside breast can be measured. Normal and abnormality of the breast will produce different electric field pattern and so does unknown capacitance (C_x). Personal computer functioned to reconstruct all of capacitance data to form an image. The required 3D ECVT algorithm was explained in other paper.[9]

2.2. Capacitance to Voltage Circuit

The capacitance signals from electrodes pairs need to be converted into voltage for further process using an electronic circuitry namely capacitance-to-voltage (C–V) circuit. The C–V circuit is built by an operational amplifier, feedback resistor, and feedback capacitor which would convert the current into ac voltage V_o (Fig. 3). C_q is stray capacitance imposed by screen sensor, cable, and electronic switches.[10] Kirchhoff law states that current entering node and leaving node is equal ($i_1 = i_2$), thus, the voltage

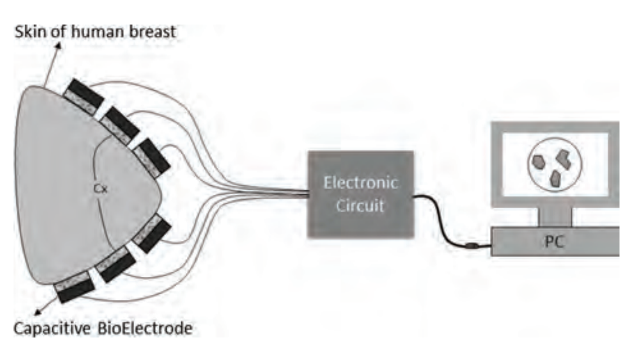


Figure 2. Block diagram of breast tissue measurement.

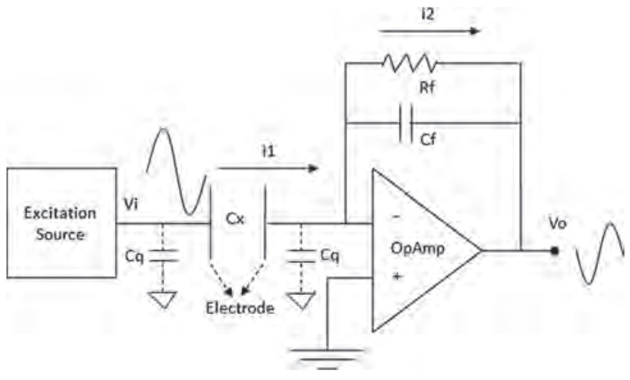


Figure 3. Basic of C–V circuit.

representing capacitance measurement can be retrieved from:

$$i_1 = i_2 \tag{1}$$

$$\frac{V_i}{Z_x} = -\frac{V_o}{Z_f} \tag{2}$$

$$\frac{V_i}{1/(j\omega C_x)} = -\frac{V_o}{R_f(1/(j\omega C_f))/(R_f + 1/(j\omega C_f))} \tag{3}$$

$$V_o = -\frac{R_f V_i (C_x/C_f)}{R_f + 1/(j\omega C_f)} \tag{4}$$

$$k = \frac{R_f}{R_f + 1/(j\omega C_f)} \tag{5}$$

where V_o is voltage output that represents capacitance measurement, V_i is sinusoidal voltage input injected to the electrode, R_f is feedback resistor, C_f is feedback capacitor, ω is angular frequency, C_x is object capacitance to be measured. This equation contains two elements i.e., capacitive and resistive.

The smaller resistance value causes greater conductivity and vice versa. In the capacitance measurement method, conductivity will be damped by setting $k \approx 1$, which can be made by selecting suitable value of R_f and C_f. Therefore the electronic circuit only measures capacitance value, and Eq. (4) can be simplified to:

$$|V_o| \cong \frac{C_x}{C_f} |V_i| \tag{6}$$

DDS (direct digital synthesizer) is used in this system as excitation source that produces continuous sine wave with its frequency which can be set from 0 Hz to 50 MHz. In addition, on the output of C–V circuit there will be bipolar wave output voltage with positive–negative value, which its peaks of signal representing capacitance measurement. The signal must be converted into DC (direct current) signal using high-speed peak detector sample-and-hold for further processing and reading by analog-to-digital conversion (ADC).[11]

3. SIGNAL PROCESSING

Signal processing is used to analyze and convert certain measured signal into another information. In this paper, signal must be converted into capacitance that represents capacitance of breast tissue. Figure 4 shows block diagram of signal processing, which consists of preconditioning (C–V circuit, initial gain, peak detector, and low pass filter) as mentioned above to convert the capacitance signals from electrodes pairs into voltages, simultaneous ADC, microcontroller, reference electrode, and serial USB. The reference electrode is a fixed plate used to measure capacitance inside the system, which will be used further for compensation against signal fluctuation caused by environmental condition such as humidity, temperature, pressure, etc.

3.1. Analog-to-Digital Conversion and Microcontroller

Analog signal from DC-restoration circuit needs to be converted into digital value using simultaneous ADC AD7606 from analog device. This chip has features such as 16-bit resolution, 200 KHz sampling rate for all channel, bipolar analog input range, voltage reference internal, and parallel output. The capacitance from all electrodes pair and be read simultaneously, thus no delay between channels.

The microcontroller used for acquiring data from simultaneous ADC, calculation into capacitance value, and send it to personal computer.

3.2. Capacitance Measurement

Capacitance to be measured between pair electrodes are not exactly C_x, but there is another parasitic capacitance or stray capacitance measured in parallel with C_x. Total capacitance $C_x + C_q$ is named standing capacitance C_s. Stray capacitance C_q can be measured when no object between pair electrode, hence the system only measure screen guard, cable, and electronic switches and then save it to register memory inside microcontroller. Capacitance C_x is obtained by subtracting standing capacitance and stray capacitance. The calculation procedures are described as:

$$C_s, C_q = \frac{V_{AD}}{G_1 V_1} C_f \tag{7}$$

$$C_x = C_s - C_q \tag{8}$$

where C_s is standing capacitance (C_x influenced by stray capacitance C_q), V_{AD} is voltage by ADC reading, C_f is capacitance feedback, G is initial gain inside C–V circuit, and C_x is measured capacitance.

4. EXPERIMENTAL RESULT

The experiment was conducted with a hemisphere 3D sensor 24 electrodes as depicted in Figure 5 that divided into three levels, each level contains eight electrode.[5] The experiment strategy is as follow: first the system

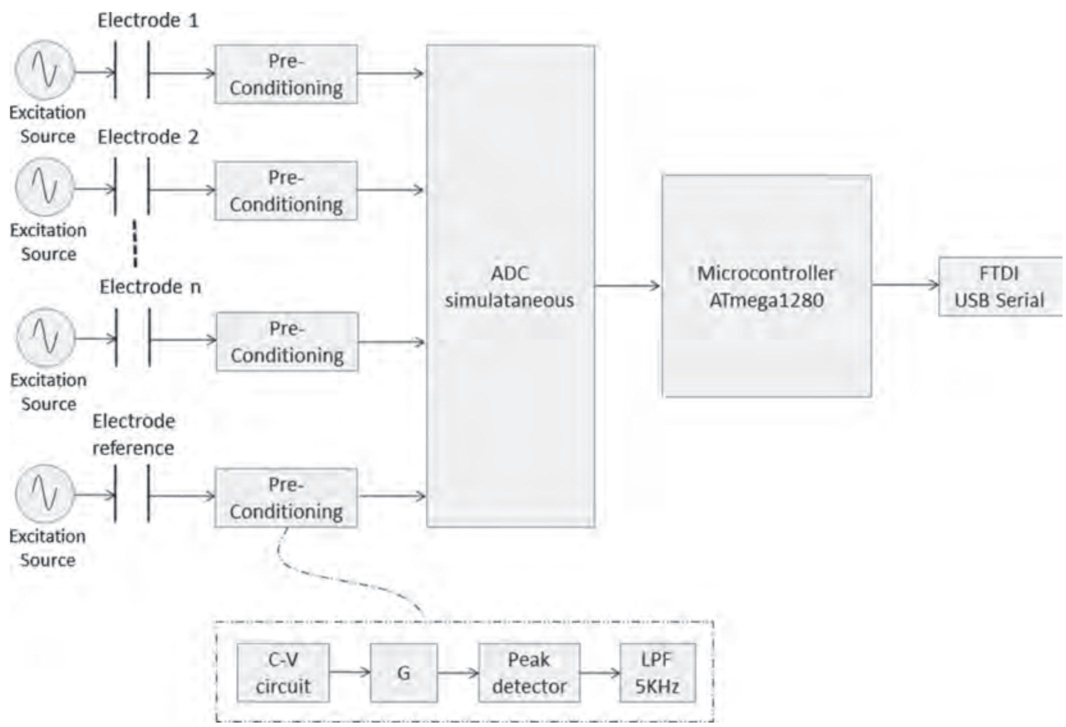


Figure 4. Block diagram of signal processing.

will calibrated using network analyser, secondly experiment using phantom 1, and the third experiment using phantom 2.

4.1. System Calibration

As initial test, two-channel capacitance measurement took place. Ceramic capacitor from 1 pF until 100 pF were used to observe resolution, sensitivity and linearity of the measurement module.

Having examined the noise level, resolution was calculated 0.1 fF with sensitivity of 1.6 V/pF. Compared with Precision Network Analyzer (PNA Agilent N5221A) measurement, linearity of the module was plotted in Figure 6 so as to introduce 2.97% error.

4.2. Experiment Using Phantom 1

Phantom in the experiment was used to describe abnormalities of the human breast. Phantom was made from paraffin ($\varepsilon_r = 2.2$) which represented fat inside the breast and small ball made from natrium chlorida (NaCl, $\varepsilon_r = 45$) with different composition to model abnormalities of breast tissue such as cancer or another lump.

Table I shows reconstruction result of phantom based on ECVT image reconstruction technique described

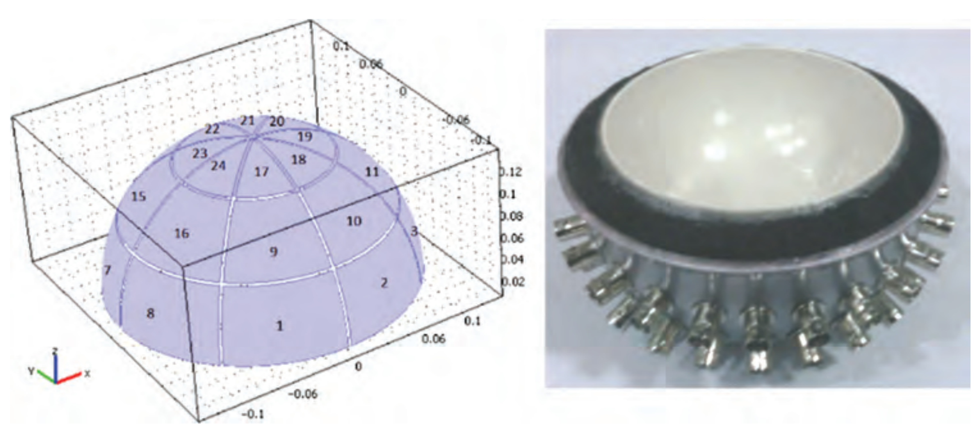


Figure 5. A hemisphere 3D sensor 24 channel: Design with unit dimensions are in meter (left), physical construction with shielding case and ports (right).

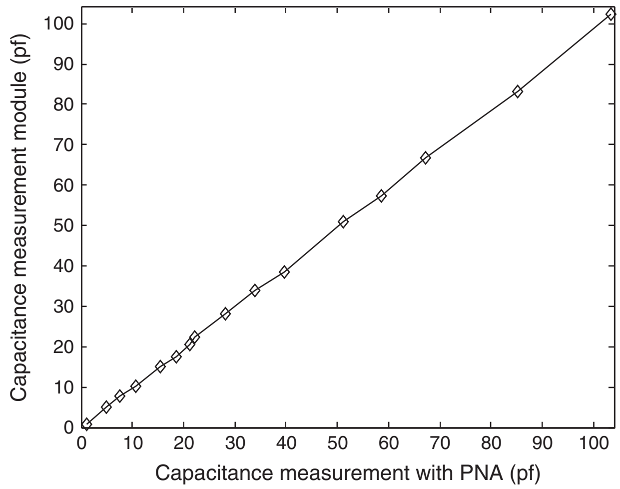
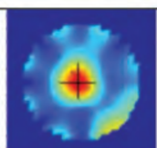
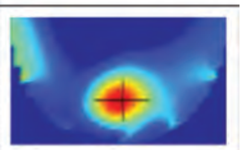
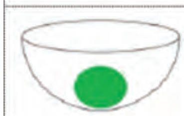
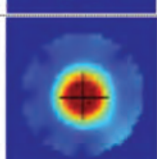
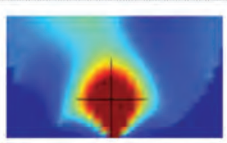
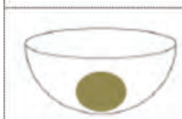
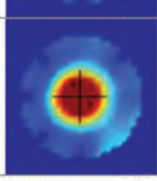
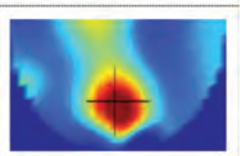
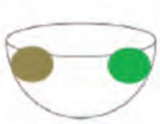
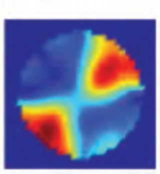
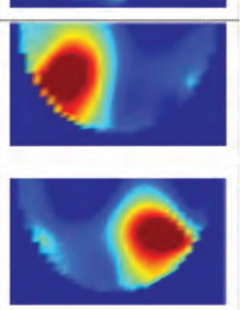


Figure 6. Comparison of measurement capacitor between system and PNA.

elsewhere.[4,5,9] The table shows in axial and lateral images using phantom with diameter 3.5 cm. For phantom detection, capacitance measurement is normalized to obtain relative capacitance using equation:

$$dn = \frac{C_r - C_l}{C_h - C_l} \tag{9}$$

Table I. Detection result using phantom 1.

Phantom	Axial images	Lateral Images
 NaCl 3gr		
 NaCl 13gr		
 NaCl 23gr		
 NaCl 13gr and 23gr		

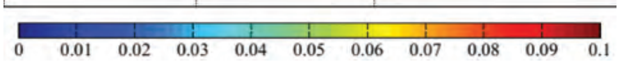


Table II. Value of normalize absolute capacitance at phantom 1.

Phantom	Sodium level (gr)	Concentrate sodium (gr/cm^3)	Detected volume (cm^3)	Detected diameter (cm)	Normalize absolute capacitance
1	3	0.134	147.95	6.561	0.0526
2	13	0.58	236.03	7.667	0.0964
3	23	1.025	245.442	7.767	0.1293
4	13 and 23	1.604	193.346	7.174	0.1699

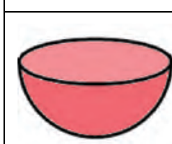
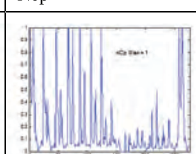
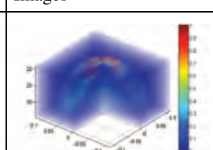
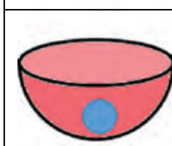
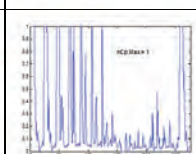
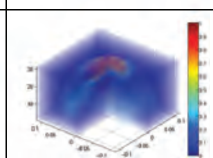
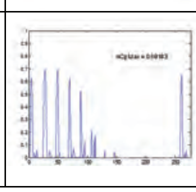
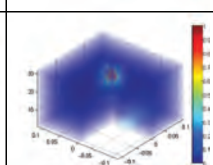
where dn is normalization result of absolute capacitance, C_r is measured capacitance, C_l and C_h are capacitance at empty calibration (sensor filled with low permittivity material) and full calibration (sensor filled with high permittivity material) respectively. Table II shows value of normalized absolute capacitance at phantom.

4.3. Experiment Using Phantom 2

The next experiment is using phantom 2 composed a wet paper tissue ($\varepsilon_r = 80$) which represented skin of the breast and small ball of NaCl ($\varepsilon_r = 45$) to model abnormalities of breast tissue such as cancer or another lump. The method is slightly different with phantom 1. When using phantom 1 the image can be shown directly because the small ball of NaCl is surrounded by paraffin with low permittivity, while using phantom 2 the image can't be shown directly because the small ball of NaCl is surrounded by wet paper tissue with high permittivity. The abnormalities of human breast (A_{ncp}) can be detected by means of subtraction the image (T_{ncp}) with normal image of breast which is represented by wet paper tissue (W_{ncp}).

$$A_{ncp} = T_{ncp} - W_{ncp} \tag{10}$$

Table III. Detection result using phantom 2.

	Ncp	Images
 (1)Wet Paper Tissue (W_{ncp})		
 (2)Wet Paper Tissue + NaCl (T_{ncp})		
Result of abnormalities (A_{ncp})		

5. CONCLUSIONS

Circuit and signal processing for capacitance measurement of breast tissue has been design and assembled. The system uses sine-wave excitation with frequency range can be adjusted from 0 KHz to 50 MHz and capable of measuring capacitance change with resolution 0.1 fF and 1.6 V/pF of sensitivity. Comparison with Precision Network Analyser (PNA) shows that the system is sufficiently accurate to measure capacitance with 0.98 of linearity. In the design, we used a reference electrode made from fixed plate to measure capacitance inside the system, which will be used further for compensation against signal fluctuation caused by environmental condition such as humidity, temperature, pressure, etc. As a result, more stable system is achieved. Based on the experiment, the system can detect abnormalities of the human breast represented by two phantoms with different condition.

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