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Design of Capacitive Sensor, Measurement and Data Acquisition System of ECVT

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***Abstract*—This paper describe new tomography acquisition design based on capacitance measurement namely Electrical Capacitance Volume Tomography (ECVT). ECVT is one of measurement instrument which is specifically used in tomography application. The acquisition instruments used 64 electrode capacitive sensors, in cylindrical shape. Measurement of capacitance is performed using charge amplifier circuit on each electrode to convert the current into voltage signal. The resulting signal represented capacitance value. To accommodate the whole 64 electrodes capacitive sensors, two data acquisition systems are developed to handle up to 32 electrodes. We also developed the communication protocol between two data acquisition systems, measured the system performance, and the speed of acquisition data.**

Keywords*—*ECVT; capacitive sensor; data acquisition system; charge amplifier circuit; communication protocol.

I. Introduction

Tomography based on capacitance measurement has been developed since '80s when Huang et. al proposed two dimensional capacitance tomography namely ECT (electrical capacitance tomography) [1]. Warsito et.al developed 2D-ECT into volumetric capacitance tomography and known as Electrical Capacitance Volume Tomography (ECVT) [2].

The principle of capacitance tomography as shown in Fig. 1 is based on injection a square wave or sine wave signal to the electrode pair resulted in fringing electric field inside the sensor. This signal is detected by other electrodes and controlled by an electronic circuit to be processed into an image using a specific reconstruction algorithm.

The image reconstruction algorithm developed rapidly and proposed by researchers as in [3, 4], as well as the development of data acquisition system [5, 6]. However, in the existing design, the maximum number of electrodes is only up to 24 to 32 composed up to four levels which is each level consist of 8 electrodes. Based on the experiments, the detected electric fields flowing in the capacitive sensor was only up to three levels. In four levels case, the Signal-to-Noise Ratio (SNR) is very small, hence it is very difficult to measure the capacitance.

To handle this issue, we proposed a new design on ECVT data acquisition system that capable to measure the capacitance using cylinder sensors up to 64 electrodes. The capacitance measurement method for the whole 64 electrodes is performed using two data acquisition systems, that each system capable to acquire data up to 32 electrodes. We applied scanning process using multilevel scanning, that 24 electrodes are activated in one time scanning. The process is performed again to the next level of scanning, until all electrodes inside the sensor are scanned.

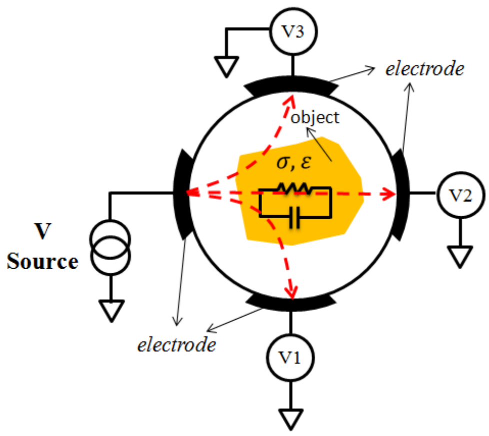

Fig. 1. Principle of capacitance tomography

II. Capacitive Sensor Design

Various geometries of the capacitance sensors have been designed to adapt the different application of ECVT system. Geometries such as hemisphere [5], helmet [7], bend, T-shape, half cylinder [8], and other geometry designs have been proposed. Our design is described in the following chapters.

A. Physical Dimension

In this research, we designed the cylindrical capacitance sensor consist of 64 capacitance electrodes that are divided into eight levels consist of 8 electrodes each as shown in Fig. 2. The electrodes are designed in shifted composition and have dimensions as follows:

- Diameter : 9 cm
- Height : 24 cm
- Material sensor : PVC (Polyvinyl Chloride)
- Thickness of sensor : 1 mm
- Material of electrode : copper sheet
- Size of electrode : 3×3 cm
- Composition : 8×8 (64 electrodes)

- Gap of electrodes : 5 mm
- Thickness of electrode : 0.1 mm
- Earth guard top&bottom : 5 cm
- Earth guard between electrode: 2 mm
- Gap between Earth guard and electrode: 1.5 mm

Electrostatic can damage the electronic circuit used to measure capacitance in the data acquisition system. To minimize the static problem, 1 MΩ resistor is attached between each electrode and earth guard [9].

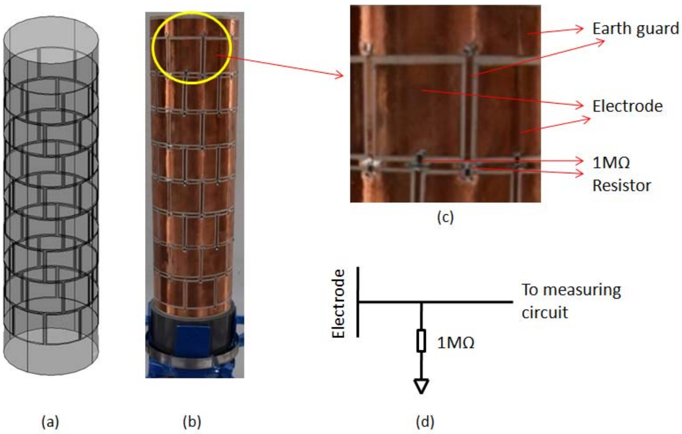

Fig. 2. Proposed capacitive sensor; (a) 8×8 sensor design (b) photograph of the sensor; (c) connection of electrodes in detail; (d) circuit diagram of each electrode

The capacitance is measured based on the principle that two parallel electrodes facing each other will have capacitance value. It depends on the geometry, size, distance, and dielectric of two electrodes. In sensor design, it can be analyzed that the distance between electrode and earth guard has also capacitance, where in tomography was known as stray capacitance. In ideal conditions, the stray capacitance of the sensor can be expressed in Eq. (1).

$$C_s = NS\frac{\varepsilon_0 \varepsilon_r A}{d} \quad (1)$$

where, C_s is stray capacitance of the sensor, N is number of electrode, S is number of side of the electrode, ε_0 is dielectric constant in vacumm 8.85 pFm^{-1}, ε_r is relative permittivity, A is area of the electrode, d is distance among electrode and earth guard, respectively. The parameters described above are then inserted in Eq. (1), so the stray capacitance can be calculated as 0.0177 pF for one electrode and 4.53 pF for all 64 electrodes.

B. Sensitivity Distribution

Sensitivity in ECVT sensor design is variation of electric field intensity in three dimensional volumetric domains (*x*,*y*,*z*). This concept related to the sensitivity variance as difference between maxima and minima of electrode pair and absolute sensitivity strength of the total sensitivity values from all electrode pairs with respect to a certain voxel [2]. The sensitivity distribution in axial direction is shown in Fig. 3. The convergence of image reconstruction process depends on the difference variation between maximum and minimum value in one layer, and smoothness of the slope of sensitivity distribution curves along axial direction. If one layer has more variation and the slope is smoother, it could be easily converged.

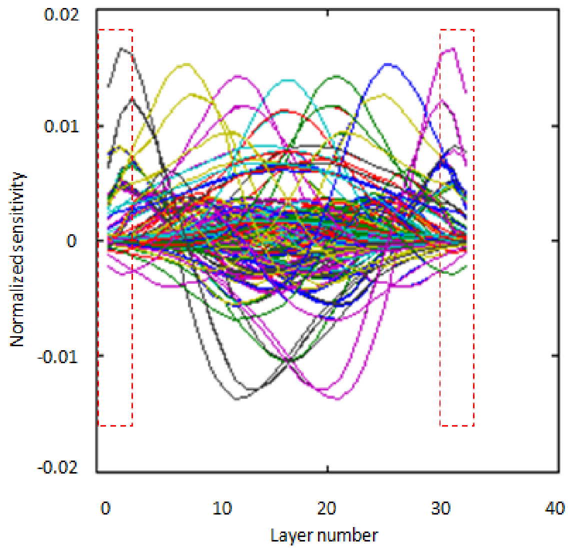

Fig. 3. Axial distribution of normalized sensitivity for all electrode pairs (the dead zones are indicated by the dashed line).

Based on Fig. 3, middle area of the sensor gives more variations, while the area marked within dashed line is "dead zone" area. This region is less varied, hence difficult to be converged and the area is located in the edge of the sensor.

III. ECVT Data Acquisition System

Data Acquisition System (DAS) is designed to acquire data from sensor, control the scanning process, and convert the analog into digital signal and send it to the Personal Computer (PC) as shown in Fig. 4 and 5. Two data acquisition systems are needed to accommodate all 64 electrodes, that each system handles 32 electrodes.

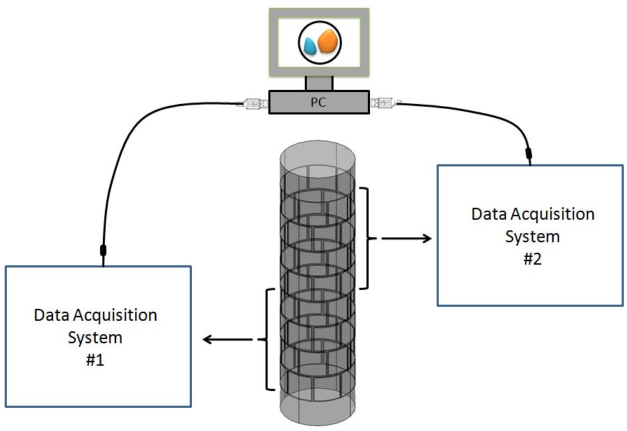

Fig. 4. Block diagram of ECVT Data Acquisition System

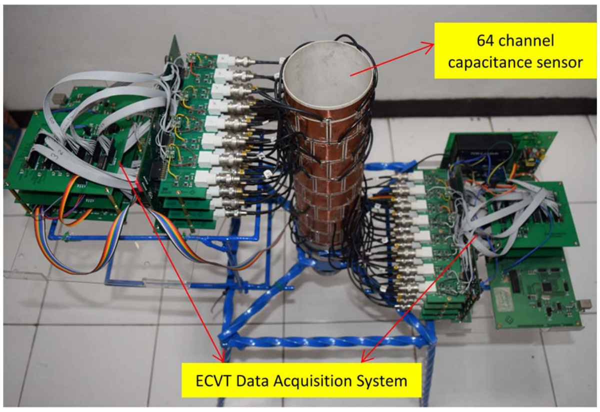

Fig. 5. Photograph of the ECVT Data Acquisition System

A. Measuring Method

The capacitance measurement of 64 channels ECVT sensor is divided into two identical DAS that each DAS functioned as illustrated in block diagram in Fig. 6. The first 32 electrodes of sensor were connected to the first DAS through analog switch which each channel/electrode is connected to single charge amplifier circuit. The output of each charge amplifier circuit is then connected to the multiplexer (MUX) and peak detector circuit to obtain the magnitude of the signal. The signals are then amplified by an analog amplifier (Gain) and convert it into digital signal by using Analog-to-Digital Converter (ADC).

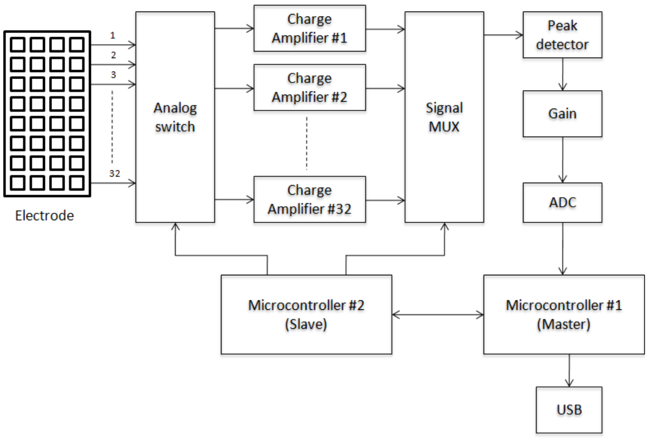

Fig. 6. Block diagram of measuring method for each DAS

Each DAS has two microcontrollers (Master and Slave) with specific purposes due to a large number of electronic components that should be addressed, while the microcontroller has limited ports. The Slave microcontroller handles analog switch and signal MUX that arrange signal path from sensor to the ADC. The Master microcontroller handles the digitalization process, signal processing, data sending to the PC through USB, and controlling the Slave microcontroller. The method of converting the capacitance signal to the voltage in charge amplifier circuit was proposed in [5], while the function of analog switches was proposed in [10].

B. Communication Protocol

A signal control is required to communicate between Master and Slave microcontrollers. The signal control is designed as simple as possible that consists only enable, clock, and data commands. The communication between both of microcontrollers used a single port, which the Slave is in condition standby when ready to receive the signals from Master as seen in Fig. 7(a). The "enable" function is used to activate the Slave microcontroller slave, while the "clock" function is used to control the 8-bit data sending command.

Figure 7(b) showed the timing diagram of signal control that is used to communicate between microcontrollers. The data packet has 4 bytes, that each byte has 8 bits. The first data is command, followed byD1 and D2 as the data that will be sent, and to end the packet, an asterisk '*' character is used. The communication is activated when the enable signal is 'zero'. The 4 bytes packet data will be sent to microcontroller slave at the time of clock transitions from high to low or low to high (toggle). Accordingly, sending 4 bytes data packet only needs 2 clock periods that each time is: $t_1 = t_5 = 4\mu s$, and $t_2 = t_3 = t_4 = 7\mu s$. Signal "CMD" is a command that has value of 0 to 2 which functioned as: 0: all switches are off; 1: sensor testing; and 2: scanning process.

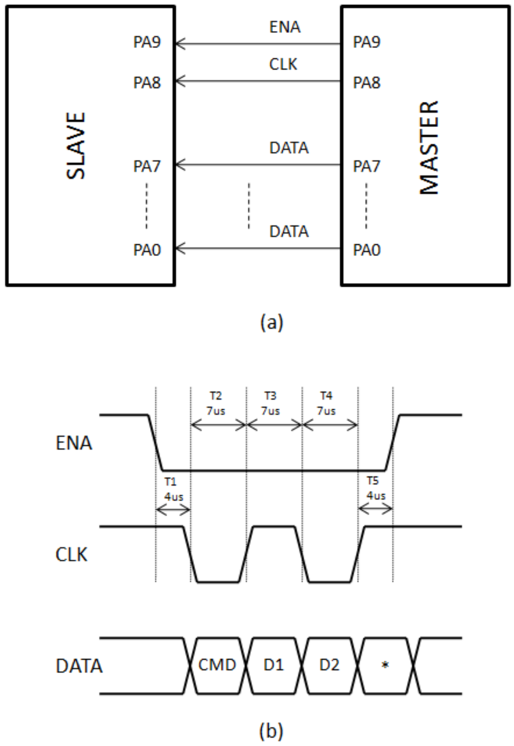

Fig. 7. Protocol communication between Master and Slave microcontrollers; (a) Block diagram; (b) Timing diagram of signal control

The communication protocol that has been described above is used between two microcontrollers in one Data Acquisition System. There is another protocol communication needed to arrange the scanning process in two DASs. The arrangement of these systems is controlled by the PC using a scanning control program in Matlab.

IV. RESULTS AND ANALISYS

The ECVT sensor and DAS have been tested to evaluate the performance of the system. Experiments were conducted to measure parameters such as resolution, SNR, dynamic range, etc. The measurement results are presented in Table 1. In the measuring of parameters, the experiment is done repeatedly 100 times. According to the data, then calculated the noise, error, resolution, SNR, and dynamic range of system measurement. These parameters are very important to determine the performance of the system so that it can be known the limitation of experiments to be performed.

TABLE I. THE PARAMETERS MEASUREMENT

Parameters	Average Values
Excitation signal	20 Vpp
Dynamic range	0 - 15 pF
Resolution	9.8 fF (femto farad)
Accuracy (mean absolute error)	0.25
Noise level (standard deviation)	33.85 mV
Signal to Noise Ratio (SNR)	48.5 dB

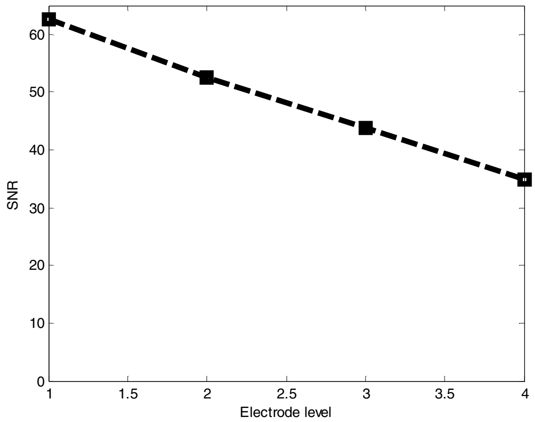

Fig. 8. Comparison of SNR value for each electrode level

The comparison of SNR value for each electrode levels has shown in Fig.8, which has measured on electrode level 1, 2, 3, and 4. The first level gives SNR value of 62.5dB, the second level gives SNR value of 52.6dB, the third level gives SNR value of 43.8dB, and fourth level gives SNR value 34.8dB. The mean of SNR value for all electrodes is around 48.5dB. Based on the graph shows that the fourth level of electrode is difficult to measure the capacitance signal. Hence, only first to third level of electrode gives a good measurement.

The speed of data acquisition of ECVT is influenced by factors such as switching time, data conversion, settling time of charge amplifier circuit, settling time of analog circuit, speed of signal processing, and speed of transfer data to PC. All of these elements are multiplied with the number of data measurement in the whole scanning process as expressed in Eq. (2).

$$T_{DAS} = N[t_{sw} + t_{set} + t_{conv} + t_{com} + t_{ctrl}] \quad (2)$$

where N is number of data measurement in whole scanning process, t_{sw} is speed of analog switch, t_{set} is settling time of charge amplifier and analog circuit, t_{conv} is conversion time of ADC, t_{ctrl} is time of signal processing in microcontroller.

To increase the speed of data acquisition, the design optimization of each process needs to be considered [11]. According to our simulation, the speed of each process is obtained as follows: t_{sw}=t_{on}=255ns; t_{off}=135ns; t_{set}=5µs; t_{conv}= 25µs; t_{com}= 86µs; t_{ctrl}= 800µs. Thus, the total time needed to acquire data is 916.39µs. In total, acquisition time scanning process is about 3.03s.

Capacitance reading retrieved from electrode pair 1-2, 1-3, .., 1-24, 2-3, 2-4, .., 2-24, 3-4, 3-5, 3-6, .., 3-24, so on until 23-24. As described before, the electric field will be flowing inside capacitance sensor from excitation to detection electrode. The closer the electrodes pair the more electric field flowing and easier to measure. However, the greater the distance of the electrode pair the less electric field flowing and more difficult to measure. The sensor with cylinder shape, the electric field can be measured by detection circuit only up to three levels or only up to 24 electrodes.

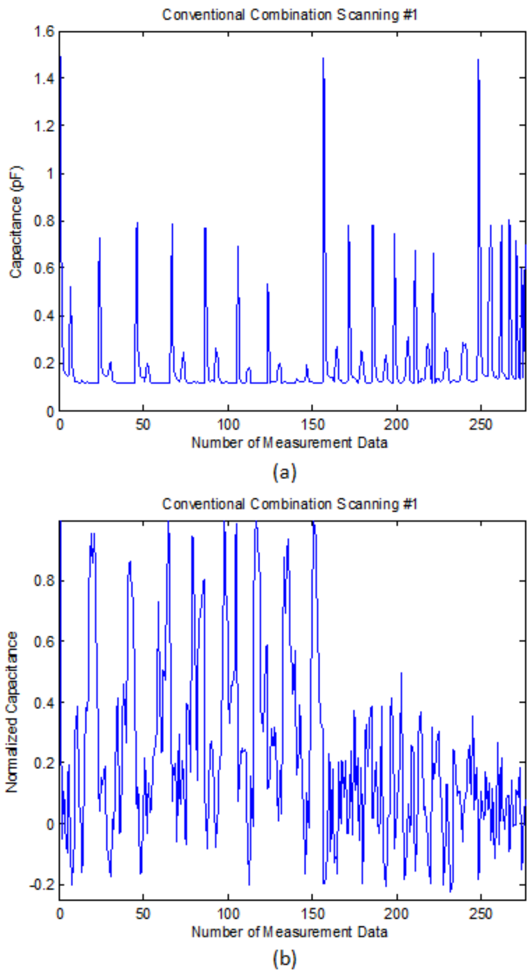

Fig. 9. Signals measurement for first 24 electrodes scanning; (a) Capacitance signal; (b) Normalized capacitance

The signal measurement of 64 channels ECVT sensor resulted in a large number of data; the number of data obtained is 6×276 data. An example of measured data for first level scanning is shown in Fig. 9. The measured data of other levels have similar pattern, but with different values. The capacitance is measured in picofarads (pF). As shown in Fig. 9, the adjacent electrode pair (electrode number 1 and number 2) give capacitance value around 1.5 pF, while the opposite electrode pair (electrode number 1 and number 5) give lower capacitance value around 0.15 pF.

Since the capacitance data still contains stray capacitance, normalization is needed before further processing using Eq. (3).

$$nc = \frac{C_r - C_l}{C_l} \tag{3}$$

Where, nc is normalized capacitance, C_r is capacitance measurement, C_l is capacitance at early measurement which the sensor has not fill with object. The normalized capacitance as shown in Fig. 9(b) represented the permittivity distribution inside sensor.

The average of signal-to-noise ratio (SNR) gives 48.5dB. Modification of charge amplifier circuit on the front end circuit and putting it as close as possible to the electrode will increase the SNR value. The speed of data acquisition system is slow enough, so that the system is only capable of being used to scan of static objects. The speed could be increase by replacing the microcontroller by using high speed processor.

V. Conclusion

We proposed a 64 channel capacitive sensor, Data Acquisition System (DAS) and the measurement method that used for Electrical Capacitance Volume Tomography (ECVT) application. Based on our results, the system capable measure of capacitance in the range up to 15 pF with resolution of 9.8 fF, and SNR of 48.5dB. The acquisition time to retrieved all data from sensor is about 3.03s, so that the system is only capable used to scan of static objects.

Acknowledgment

The author would like to thank all parties who kindly contributed to this research: Al-Musfi Saputra, Warsito P. Taruno, and Wahyu Widada from CTECH Labs Edwar Technology. This work was supported by a grant from Hibah PITTA DRPM Universitas Indonesia Grand Number: 723/UN2.R3.1/HKP.05.00/2017.

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