Signal Measurement Consistency of ECVT Data Acquisition System using Capacitor Array

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Abstract**—**This research relates to tomography based on capacitance measurement namely Electrical Capacitance Volume Tomography (ECVT). The paper discusses the design of ECVT data acquisition system that has frequent problems in measurement, such as error in signal measurement and fabrication errors. Based on those issue, development of an equipment that can help check the data acquisition system by using dummy capacitor array is proposed. In signal measurement, there are two modes: first without using array capacitor and second using capacitor array. By using a simple algorithm that refers to the measurement strategy, it is possible to immediately know which channel pair is experiencing problem. Measurement consistency on each channel is analyzed using the correlation coefficient (R) resulting an average value of 0.9387.

Keywords—ECVT; capacitive sensor; data acquisition system; charge amplifier circuit; capacitor array.

I. Introduction

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

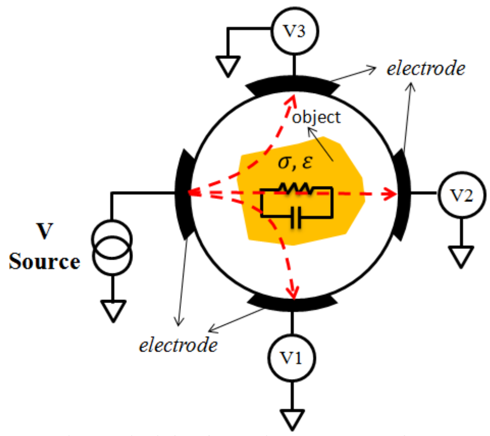


Fig 1. Principle of capacitance tomography

Currently, the ECVT data acquisition system has been developed accommodating 12, 16, 24, and up to 32 channels, in which each channel shall measure the capacitance independently [2]–[4]. Experiment that utilizes measurement from capacitive sensor often find some problems, i.e. missing data from ADC, output signal of charge amplifier are not present (too small) or even saturating circuit. Several researchers have attempted to improve the accuracy and reliability of the data acquisition system by optimizing the geometry of the capacitive sensor [5], adjusting the electrode configuration [6], reducing the effect of stray capacitance on analog switches [7], as well as quadrature phase detection [8].

According to the above issues, this paper proposes an equipment that can help in checking the data acquisition system by using dummy capacitor array. The array capacitor is made for eight electrode to check the measurement accuracy. Observation divided into four stage: first stage for first level, and then the array capacitor is moved to the next eight electrode at the second level, and so on up to the fourth level. Simple algorithm is employed to analyze the measurement in data analysis software to determine the signal consistency for all channels.

II. Design

The ECVT data acquisition system has several main parts. The front end circuit contains analog switch configuration and charge amplifier circuit. Further stages are multiplexer circuit and subsequent digital signal processing circuit. Array of capacitors are designed in series and connected to the data acquisition system as shown in Fig. 2.

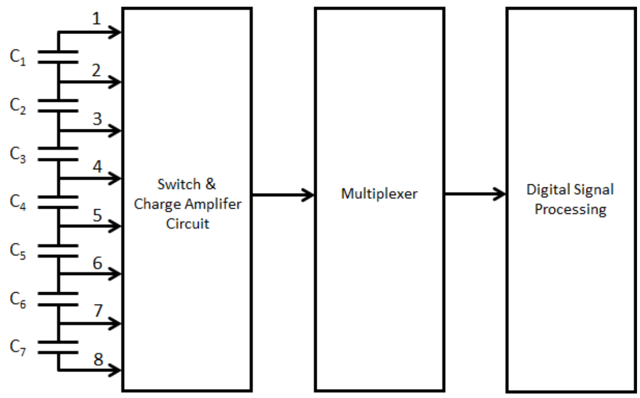


Fig 2. Design of equipment test using dummy capacitor array

As described above, the data acquisition system has maximum 32 channels, so as to test the system, four stages are required, with each stage consists of 8 channels. The system is tested in forward and reversed mode, hence 28 measurement data will be obtained as shown in Table 1.

TABLE I. MEASUREMENT STRATEGY USING FORWARD AND REVERSED MODE

No	Data	Forward	Reversed
1	V_1	1-2	2-1
2	V_2	2-3	3-2
3	V_3	3-4	4-3
4	V_4	4-5	5-4
5	V_5	5-6	6-5
6	V_6	6-7	7-6
7	V_7	7-8	8-7
8	V_8	9-10	10-9
9	V_9	10-11	11-10
10	V_{10}	11-12	12-11
11	V_{11}	12-13	13-12
12	V_{12}	13-14	14-13
13	V_{13}	14-15	15-14
14	V_{14}	15-16	16-15
15	V_{15}	17-18	18-17
16	V_{16}	18-19	19-18
17	V_{17}	19-20	20-19
18	V_{18}	20-21	21-20
19	V_{19}	21-22	22-21
20	V_{20}	22-23	23-22
21	V_{21}	23-24	24-23
22	V_{22}	25-26	26-25
23	V_{23}	26-27	27-26
24	V_{24}	27-28	28-27
25	V_{25}	28-29	29-28
26	V_{26}	29-30	30-29
27	V_{27}	30-31	31-30
28	V_{28}	31-32	32-31

III. SIGNAL MEASUREMENT

The basic principle of measuring capacitance in ECVT is using charge amplifier circuit as shown in Fig. 3, which consists of an Operational Amplifier (Op-Amp) and feedback components such as resistor R_f and capacitor C_f. $V_i(t)$ and $V_o(t)$ are sine wave signal input and output respectively, C_x is object capacitance measured in the sensor, whereas C_{s1} and C_{s2} are stray capacitances which are also measurable in the system. Stray capacitance is parasitic signal derived from other source such as from coaxial cable, screen sensor, and the effect of analog switches used to selecting electrode pair [9].

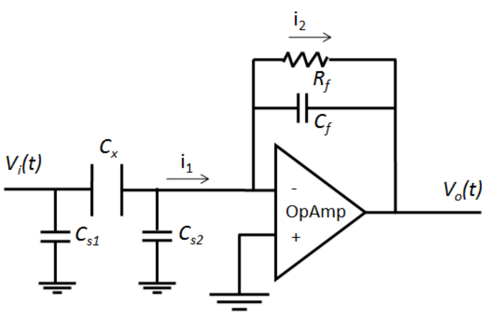


Fig 3. Charge amplifier circuit

Kirchhoff's law state that the current flowing to a point and the current flowing away from the point is the same $(i_1 = i_2)$, so that the output signal from this circuit is known. There are two methods of measuring capacitance, first by measuring the amplitude signal at the Op-Amp output, second, by measuring the phase difference between the excitation and the detection signal. The measurement capacitance utilizing the amplitude signal as described in this paper is shown in Eq. (1) and (2):

$$V_o = -k\frac{C_s}{C_f}V_i \quad (1)$$

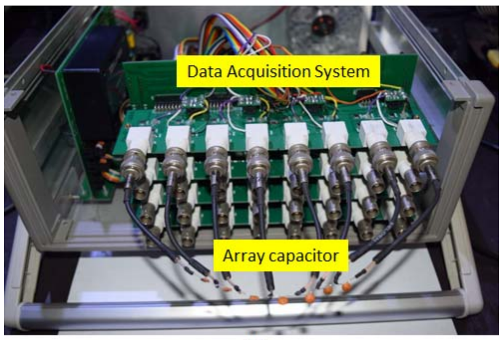
$$k = \frac{R_f}{R_f + {}^{1}/_{\omega C_f}} \quad (2)$$

where V_i is excitation signal input, V_o is signal output, R_f is feedback resistance, C_f is feedback capacitance, C_s is capacitance to be measured inside sensor, and ω is angular frequency [10].

IV. RESULTS AND ANALISYS

There are two modes in signal measurement. First, initial measurement without capacitor array to find out how much stray capacitance in the data acquisition system. Second, measurement with dummy capacitor array to test the capability of measuring capacitive sensor appropriately. Experimental setup of ECVT data acquisition system using a dummy capacitor array is shown in Figure 4. In the following experiment, ECVT data acquisition system acquires data up to 32 channels which are divided into four levels with each level containing 8 channels. The capacitive sensor model uses dummy capacitor array with a fixed value of 1 pF.

(a)



(b)

Fig 4. Measurement using dummy capacitor array

A. Measuring signal without dummy capacitor array

The input of data acquisition system on floating (not connected) is described as signal measurement without capacitor array. The purpose of the measurement with this mode is to find out how much stray capacitance in the data acquisition system. Stray capacitance constantly presents in the measurement system due to the influence of several factors such as the coaxial cable, the analog switch, and also signal interference from the electronic circuit. Measurements are done for each channel from channel 1 to channel 32 either forward or reversed. The forward measurement means the excitation voltage is distributed to the lower channel of each active electrode pair, while the other channel act as a detection. Examples are 1-2, 2-3, 3-4, 4-5, 5-6, etc. The reverse measurement means the voltage polarity is reversed, the excitation voltage is distributed to the upper channel of each active electrode pair, while the other channel act as a detection. Examples are 2-1, 3-2, 4-3, 5-4, 6-5, etc.

The measurement results are shown in Fig. 5 through 8, where each figure has two graphs: forward and reversed measurement. The 32 channel data acquisition system being used has four levels, each level contain eight channels. The first stage is measured at level one to obtain 7 data, then next level until fourth level so that 28 data measurement are obtained. A good system will produce measurable voltages and capacitances that have similar values, without significant signal spikes.

Figure 5 and 6 illustrate an example of inconsistent measurement with error in some channels. Figure 5 shows the output voltage of the charge amplifier circuit while Fig. 6 is the voltage data that has been converted to capacitance. According to the graph of measurement at first level (first 8 channel), good performance occurs where there is no error for either forward or reversed due to average signal uniformity in both voltage and capacitance. However, there are signal spikes on some channels. Measurement errors occur on the forward mode at level 2 on channel pair 10-11 and 12-13. While in reversed mode, there are errors at levels 3 and 4 for almost all channels due to the signal amplitude is greater than the normal level.

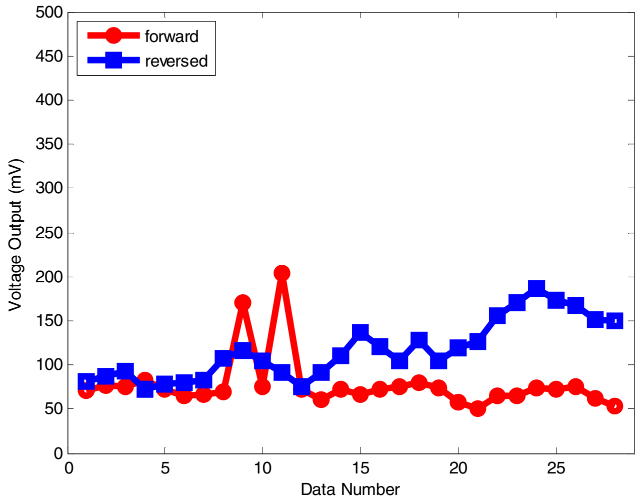


Fig 5. Inconsistency measurement of voltage output

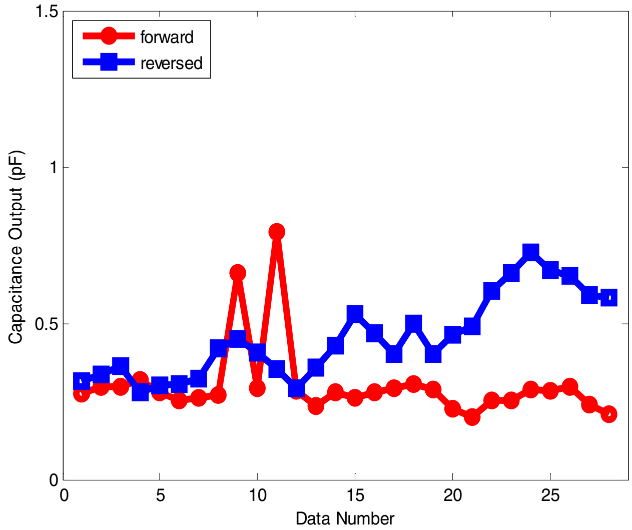


Fig 6. Voltage data converted to capacitance

Figure 7 and 8 show consistent measurement for all channel pairs with no error. In normal circumstances, the average voltage level will show 60-75 mV for both forward and reversed, or 250 fF (femto farad) after conversion into capacitance.

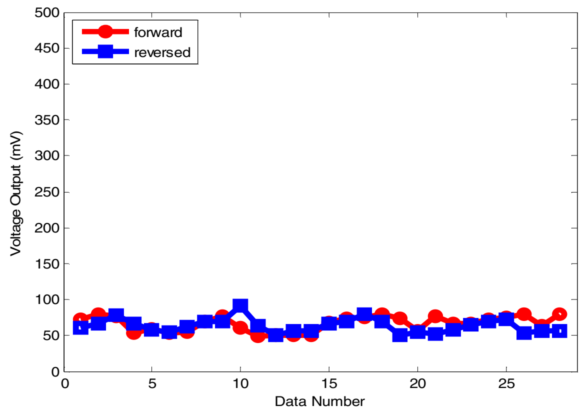


Fig 7. Consistency measurement of voltage output

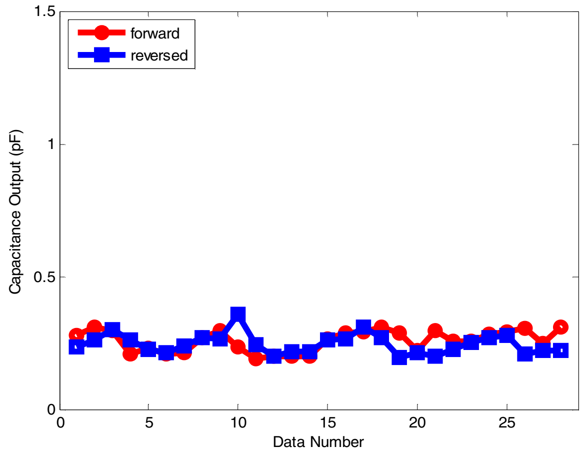


Fig 8. Voltage data converted to capacitance

B. *Measuring signal using dummy capacitor array*

Measurements using dummy capacitors array are performed to find out whether the ECVT data acquisition system is capable of measuring capacitive sensor appropriately. In this study, dummy capacitor array of 1pf is used. Measurements are done for each channel in both forward and reversed modes. The results of the measurements are shown in Fig. 9 to 12, where each figure has two graphs: forward and reversed measurement.

Figure 9 and 10 illustrate an example of inconsistent measurement with error in some channels. Figure 9 shows the output voltage of the charge amplifier circuit while Fig. 10 is the voltage data that has been converted to capacitance. According to the graph, the measurement at first level, second level, and third level are in agreement and there is no error either forward or reversed due the average signal uniformity for both voltage and capacitance. However, there are signal spikes on some channels. Measurement errors occur on the forward mode at level 4 on channel pair 28-29, 30-31 and 31-32. While in reversed mode, there are errors at level 4 on channel pair 29-28, 30-29, and 32-31. The result of capacitance measurement should approach dummy capacitor value about 1 pF, but since there are errors in some channels, it shows a considerably higher capacitance value of about 7 pF.

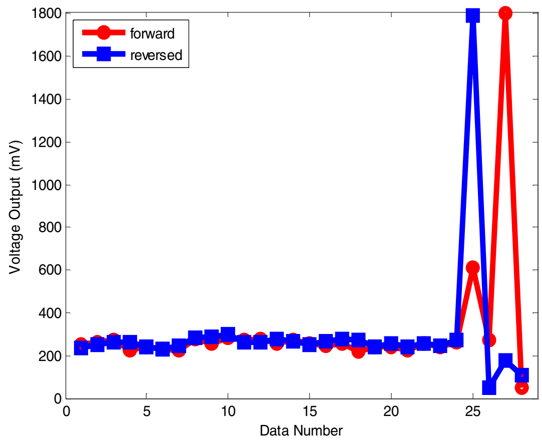


Fig 9. Inconsistency measurement of voltage output

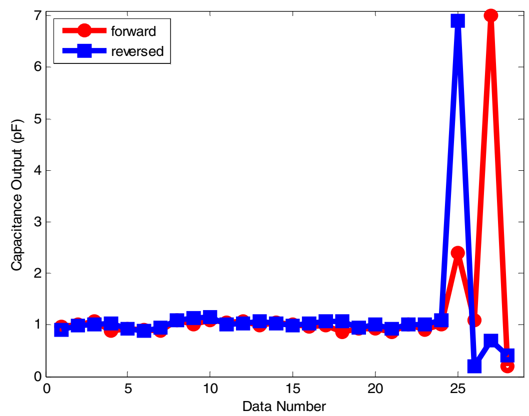


Fig 10. Voltage data converted to capacitance

Figure 11 and 12 show consistent measurement for all channel pairs with no error. In normal circumstances, the average voltage level will show 250 mV for both forward and reversed. The average value of capacitance measured by the system is about 1 pF for both the forward and reversed modes.

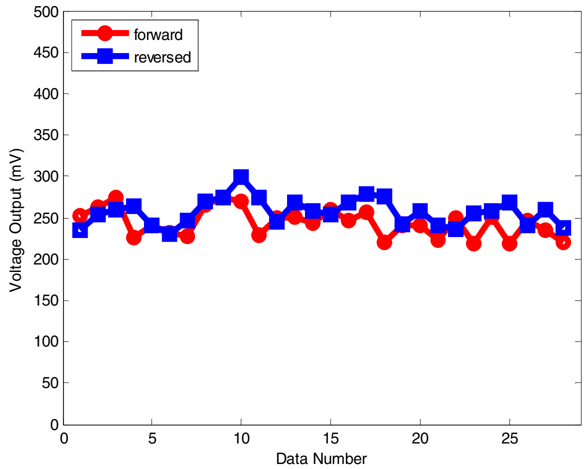


Fig 11. Consistency measurement of voltage output

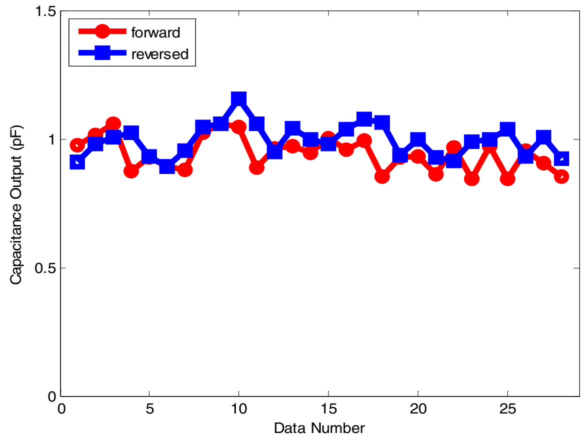


Fig 12. Voltage data converted to capacitance

C. *Measurement consistency*

Based on measurement signal of ECVT data acquisition system using dummy capacitor, the consistency of each channel is examined. The analysis method is coefficient correlation (R) by comparing the measurement results obtained by the system with dummy capacitor. The results of coefficient correlation are shown in Fig. 13 illustrating graphs in both forward and reversed modes. According to the graph, the value of coefficient correlation is close to 1 with an average of 0.9387. This indicates that the ECVT data acquisition system is reliable for use in practical applications, such as measuring the capacitive sensor.

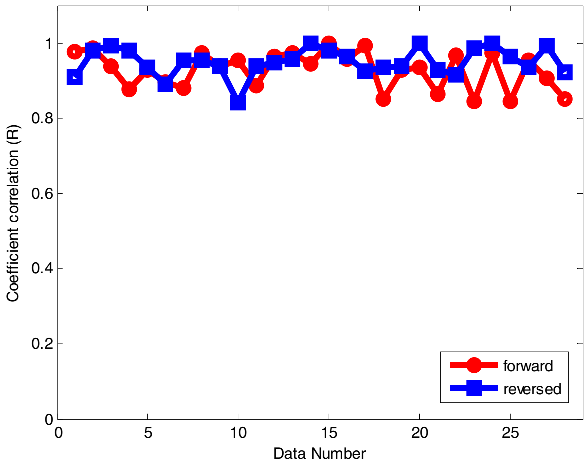


Fig 13. Coefficient Correlation (R) for dummy capacitor array measurement

V. CONCLUSION

ECVT data acquisition system has important requirement to ensure the uniformity of output signal. Signal spikes on some channels indicate error on specific channel pair, so that the measurement channel should be mitigated. This method has been tested using ECVT 32 channel data acquisition system. By using a simple algorithm that refers to the measurement strategy in Table 1, it is possible to immediately know which channel pair is experiencing problem. Measurement consistency of the system can be analyzed using correlation to assess the reliability of the system for practical application.

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