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A High-speed Digital Electrical Capacitance Tomography System Combining Digital Recursive Demodulation and Parallel Capacitance Measurement

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Abstract- Two means can be used to improve the data acquisition rate of the ECT system with a fixed excitation frequency, i.e. improving the capacitance measurement speed or changing the capacitance measurement mode from serial to parallel. This paper presents a newly developed high-speed electrical capacitance tomography (ECT) system by combining digital recursive demodulation and parallel-mode capacitance measurement methods. By using the digital recursive demodulator, the time-cost for one time of capacitance measurement can be one period of the excitation sinusoid or less. By using the parallel-mode capacitance measuring unit, capacitances between the exciting electrode and all other measuring electrodes can be measured simultaneously. The data acquisition rate of the parallel-mode ECT system with a sensor of N electrodes is $N-1$ times of a traditional serial-mode ECT system with the same excitation frequency. When the excitation frequency is 100 kHz and 0.6 periods of data are used for signal demodulation, the data acquisition rate can reach up to 15150 frames per second. The developed system together with a heat-resisting circular ECT sensor with 12 electrodes was used to monitor the ignition process of a cylindrical flame generated by a Bunsen burner. Experimental results show that the ECT system can locate the position and capture the dynamic process of the flame with a high temporal resolution.

Keywords- Electrical capacitance tomography; Capacitance measuring unit; Digital demodulation; Flame monitoring

I. INTRODUCTION

Electrical Capacitance Tomography (ECT) is an imaging technique to obtain the permittivity distribution in the interior of an object from external capacitance measurements [1], [2]. A typical ECT system consists of three main units: 1) an ECT sensor, 2) a data acquisition unit, and 3) a computer for image reconstruction. Compared with other process tomography techniques, such as ultrasound, optics, X-ray and gamma-ray, it has several advantages, including low cost, rapid response, good portability, radiation-free and good

robustness [3], [4]. The ECT technique has been used for parameter measurement and process monitoring for industrial applications, e.g., two-phase flow [5], pneumatic conveying [6], fluidized beds [7], and flame monitoring [8].

When an ECT system is used to monitor a rapidly-changing process, e.g., an ignition process of a flame which is typically a pulsating process, or used for velocity measurement, high-speed data acquisition is required to provide high temporal resolution [3], [9]-[12]. For example, when the ECT system is used to study the pulsating characteristics of the flame in the pulse combustor whose pulsation frequency is about 200 Hz [13], a data acquisition rate faster than about 400 frames per second is required for an ECT system to capture the basic frequency information of the flame. However, a faster data acquisition rate, e.g. thousands of frames per second, is required for the ECT system to capture faster temporal details of the pulsating flame, such as the discharge process of the pulse ignitor.

To improve the data acquisition rate of the ECT system with a fixed excitation frequency, we can either improve the capacitance measurement speed or change the capacitance measurement mode from serial to parallel.

Researchers made effort to improve capacitance measuring circuits [3], [14], [15]. The basic capacitance measurement methods proposed for ECT in the literatures include charge-discharge method, single-shot high-voltage (SSHV) method and AC-based method. By using the charge-discharge method, an ECT system was developed in [16] with a capacitance measurement rate of 6600 times per second, a data acquisition rate of 100 frames per second and a resolution of 0.3 fF for a 12-electrode sensor. The data acquisition rate was increased to 800 frames per second by using a differential sampling method [17]. By using the SSHV method in [18], the capacitance measurement rate can reach up to 20000 per second, the data acquisition rate of the ECT system is 1200 frames per second for a 16-electrode sensor and the SNR is 42.2 dB for 95.7 fF.

Since Yang presented an AC-based high-precision high-frequency capacitance measuring circuit in 1994 [2], it has been widely used for developing ECT systems. The AC-based capacitance measurement circuit is firstly

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constructed by using analog devices. The excitation signal generated by the Direct Digital Synthesis (DDS) technique is applied on an excitation electrode and another electrode is connected to a capacitance-to-voltage (C/V) converter. Then the output signal of the C/V converter is multiplied by a quadrature reference signal and filtered by a low pass filter (LPF) to obtain a DC signal that is proportional to the capacitance. Finally, the DC signal is sampled by an Analog-to-Digital Converter (ADC) to obtain a digital value. The analog device-based capacitance measuring circuit has been successfully applied in ECT. If the excitation frequency is 500 kHz and the cut-off frequency is 5 kHz, the capacitance measurement time is 200 μ s and the data acquisition rate is higher than 100 frames per second [19]. However, if the parameters of the analogue filter are fixed, the demodulation speed is mainly limited by the cut-off frequency.

In recent years, researchers constructed digital demodulators for sinusoid signal by using high-performance digital processing devices, such as Complex Programmable Logic Device (CPLD), Field Programmable Gate Array (FPGA) and Digital Signal Processor (DSP) [20], [21]. When the digital demodulator is used in an ECT system, the structure of the ECT system can be simplified. Digital demodulation is implemented using programmable devices or software running in a digital processing device. Usually, a digital demodulation method requires the sampled data in an integer signal period, e.g. the rectification demodulation method [21] and quadrature demodulation method [22]. A digital recursive demodulation method was proposed for using sampled data in less than a complete period to improve the demodulation speed but at an expense of Signal-to-Noise Ratio (SNR) [23]. By using a digital demodulation method, a demodulation result can be obtained by using data in one or less than one signal period to greatly improve the capacitance measurement speed. The data acquisition rate of a high-performance ECT system based on the digital demodulation method in [3] is 1541 frames per second and the SNR is 60.3 dB.

As for the capacitance measurement mode for ECT, the serial mode is widely used [3], [21], [23], [24]. In this mode, the capacitances of an N -electrode sensor are measured by using one capacitance measuring circuit and multiple CMOS switches. The configuration is simple and low-cost. However, the capacitance between every two electrodes in an ECT sensor needs to be measured one after another and a delay time is required after electrode switching to reduce the influence of switching oscillations on the circuit. Therefore, the serial mode capacitance measuring circuit for ECT is slow and cannot satisfy the requirement of rapidly-changing processes. A parallel-mode capacitance measurement method can be used to improve the speed [25], [26], i.e., capacitances between the exciting electrode and all other $N-1$ measuring electrodes are measured simultaneously.

Our research group has developed a digital serial-mode

ECT system [21], [27]. In this paper, a digital parallel-mode ECT system was proposed to achieve higher data acquisition rate and used for flame monitoring. The main purpose of this paper is to develop a high-speed ECT system by combining the digital recursive demodulation and parallel-mode capacitance measurement methods. The proposed ECT system can be used to capture rapidly-changing processes because of its high data acquisition rate. The data acquisition rate of the proposed parallel-mode ECT system can be $N-1$ times of the corresponding serial-mode ECT system.

This paper is organized as follows. In Section II, the system design is presented. Section III is devoted to test and analyze the performance of the proposed system. Section IV describes the experiments and results of flame monitoring. Section V concludes the research outcomes.

II. SYSTEM DESIGN

The parallel-mode ECT system hardware is divided into two main parts: a capacitance measuring unit and a control unit. The capacitance measuring unit is used for C/V conversion and signal demodulation. The control unit is used for excitation signal generation, channel selection and data transmission from the circuit to the host computer.

A. Capacitance measuring circuit

The widely-used AC-based method is used for capacitance measurement. The AC-based C/V converter is shown in Fig. 1,

Fig. 1. C/V converter.

where A_1 is an operational amplifier, C_x is the capacitance being measured, R_f and C_f are the feedback resistance and capacitance, and C_{s1} and C_{s2} are the stray capacitances. The output voltage of the C/V converter can be expressed as

$$V(t) = -\frac{j\omega C_x R_f}{j\omega C_f R_f + 1} \cdot V_i(t), \quad (1)$$

where $V_i(t)$ and $V(t)$ are the input and output signals, ω is the angular frequency. When the excitation frequency is fixed as 100 kHz and the amplitude of $V_i(t)$, A_i , is fixed as $20 V_{p-p}$, the amplitude of the output signal is proportional to the measured capacitance. In [27], the C/V converter has been analyzed in detail. In this paper, the feedback resistance and capacitance are selected as 33 k Ω and 4.4 pF, respectively. Then the maximum capacitance to be measured is 4 pF and the sensitivity of the C/V converter is 0.5 V_{p-p}/pF .

The output signal of the C/V converter can be expressed as

$$V(t) = A \sin(\omega t + \varphi), \quad (2)$$

where A , ω and φ are the amplitude, angular frequency and phase of the signal, respectively. When the signal is sampled

by a high-speed ADC with a sampling frequency of f_s , its discretized form can be written as

$$V(n) = A \cos\left(\frac{2\pi n f}{f_s} + \varphi\right) \quad n = 1, 2, \dots, N, \quad (3)$$

where n is the serial number of the samples and f is the frequency of the measured signal. Then the signal can be demodulated by a digital recursive demodulator [23].

Equation (3) can be written in a matrix form:

$$V(n) = \mathbf{u}_n \cdot \mathbf{x}_n, \quad (4)$$

where $\mathbf{u}_n$ is the measurement vector that can be obtained from the known information. $\mathbf{x}$ is the state vector related to the amplitudes and phases. $\mathbf{u}_n$ and $\mathbf{x}$ are expressed as

$$\begin{cases} \mathbf{u}_n = \begin{bmatrix} e^{-j\frac{2\pi n f}{f_s}} & e^{j\frac{2\pi n f}{f_s}} \end{bmatrix}, \\ \mathbf{x}_n = \begin{bmatrix} \frac{A}{2} e^{j\varphi} & \frac{A}{2} e^{-j\varphi} \end{bmatrix}^T \end{cases}, \quad (5)$$

where the operator $[\]^T$ denotes the transpose.

When N samples are used for demodulation, the least squares method can be used to obtain an estimate of $\mathbf{x}$:

$$\mathbf{x} = \left(\begin{bmatrix} \mathbf{u}_1 \\ \mathbf{u}_2 \\ \vdots \\ \mathbf{u}_N \end{bmatrix}^T \begin{bmatrix} \mathbf{u}_1 \\ \mathbf{u}_2 \\ \vdots \\ \mathbf{u}_N \end{bmatrix} \right)^{-1} \begin{bmatrix} \mathbf{u}_1 \\ \mathbf{u}_2 \\ \vdots \\ \mathbf{u}_N \end{bmatrix}^T \begin{bmatrix} V(1) \\ V(2) \\ \vdots \\ V(N) \end{bmatrix}. \quad (6)$$

Assume that K is the inverse state-error correlation matrix and

$$K_n = [\mathbf{u}_1 \ \mathbf{u}_2 \ \dots \ \mathbf{u}_n] [\mathbf{u}_1 \ \mathbf{u}_2 \ \dots \ \mathbf{u}_n]^T. \quad (7)$$

Assume that

$$P_n = [\mathbf{u}_1 \ \mathbf{u}_2 \ \dots \ \mathbf{u}_n] [V(1) \ V(2) \ \dots \ V(n)]^T. \quad (8)$$

In the digital recursive demodulator, K and P can be initialized by

$$\begin{cases} K_1 = \mathbf{u}_1^T \mathbf{u}_1 \\ P_1 = \mathbf{u}_1^T V(1) \end{cases} \quad (9)$$

Then K_n and P_n are obtained in a recursive way:

$$\begin{cases} K_n = K_{n-1} + \mathbf{u}_n^T \mathbf{u}_n \\ P_n = P_{n-1} + \mathbf{u}_n^T V(n) \end{cases} \quad (10)$$

If N samples are used for demodulation as long as $N > 2$, the updated value of $\mathbf{x}_N$ can be obtained by

$$\mathbf{x}_N = (K_N)^{-1} (P_N). \quad (11)$$

Then the amplitude and phase of the signal can be calculated by

$$\begin{cases} A = 2 \left| \frac{A}{2} e^{j\varphi} \right| = 2 |x[1]| \\ \varphi = \arccos \left[2 \cdot \text{Re} \left(\frac{A}{2} e^{j\varphi} \right) / A \right] = \arccos \left[\frac{2 \cdot \text{Re}(x[1])}{A} \right] \end{cases}, \quad (12)$$

where $x[1]$ is the first element of $\mathbf{x}$, and $\text{Re}(x[1])$ is the real part of $x[1]$. Then the capacitance value can be calculated by:

$$C_x = \frac{A \sqrt{(\omega C_f R_f)^2 + 1}}{A_f \omega R_f}. \quad (13)$$

Compared with the widely-used digital quadrature demodulator, the digital recursive demodulator can provide greater flexibility between demodulation accuracy and speed, i.e. either to obtain a higher speed at an expense of lower accuracy, or vice versa.

B. Parallel-mode capacitance measuring unit

The parallel-mode capacitance measuring unit is shown in Fig. 2. For an N -electrode ECT sensor, N capacitance measuring channels are used, including N C/V converters, N ADC chips and $4N$ switches. Each ADC is used to sample the output signal of the corresponding C/V converter. An FPGA (EP3C25Q, Altera) is used for channel selection and signal demodulation.

Fig. 2. Schematic diagram of the parallel-mode capacitance measuring unit.

The electrodes in the ECT sensor has two working conditions, either excitation or detection. If electrode 1, denoted as E_1 , in Fig. 2 is used for excitation, switches 1 and 2, i.e. S_{11} and S_{12} , are turned on and switches 3 and 4, i.e. S_{13} and S_{14} , are turned off in channel 1. Meanwhile, switches 1 and 2 are turned off and switches 3 and 4 are turned on in channel 2 to channel N . The workflow of the capacitance measuring unit is described as follows.

1) Set the parameter values, i.e. the electrode number, N , and the demodulation time, T_d ;

2) Obtain the excitation electrode number, n_e , from the control unit;

3) Change the working conditions of the electrodes according to n_e by using the switches in the capacitance measuring unit;

4) Sample and demodulate the signals in all channels simultaneously;

5) Connect the capacitance measuring unit sequentially to the control unit by bus switches for data transmission until all the demodulated data are completely transmitted.

Here, the data transmission speed should be considered. For an ECT sensor with 12 electrodes, 66 capacitance values are required to be transmitted to the PC in one frame. One capacitance value requires 32 bits in the digital recursive demodulator. Then the required data transmission rate is about 4 MB/s for the data acquisition rate of 15150 frames per second. For the USB 2.0 device used in this paper, the maximum transmission speed is 60 MB/s in theory. Therefore, the USB 2.0 device is fast enough to transmit the required data.

C. Control unit

The control unit is shown in Fig. 3, which consists of a CPLD (EPM1270, Altera), a Digital-to-Analog Converter (DAC), an LPF and an USB interface device. The CPLD is used for channel selection, data processing and USB interface device control. A sine-wave excitation signal is generated by CPLD, DAC, and LPF based on the DDS technique. The USB device is used for data communication between the control unit and the host PC. The clocks that drive the DAC and the capacitance measuring units come from an external 40 MHz oscillator. The clocks can be accurately controlled by CPLD, which guarantees synchronization between signal excitation and acquisition. When the demodulation process in the capacitance measuring unit ends, the demodulated data are received from the capacitance measuring unit and transmitted to the PC via USB. If $N(N-1)$ capacitance values for two frames data is completely transmitted, a check bit is added for identification by software.

Fig. 3. Schematic diagram of the control unit.

D. Software

The ECT software is developed in Visual Studio, for data processing, data storage, data display and image reconstruction and display. The main functions of the software are shown in Fig.4. Control instructions, including electrode number, excitation frequency, data acquisition rate, can be transmitted to the control unit. The SNR and standard deviation are calculated and displayed online. The lower and higher calibration data, and measurement data are stored for off-line analysis. The widely used Linear Back Projection (LBP) algorithm, Landweber algorithm [28] and Calderon algorithm [29] are implemented. The images indicating the permittivity distribution can be reconstructed and displayed in different speed. The display rate can be flexibly adjusted by choosing appropriate delay time in the software. When the

software is operated in a different host PC, the display rate should be set according to the performance of the CPU and GPU of the PC.

Fig. 4. Main functions of the ECT software.

III. CALIBRATION AND PERFORMANCE ANALYSIS

A. Calibration of capacitance measuring circuit

The capacitance measuring unit was calibrated using a high-precision impedance analyzer (Model: 4294A), from Agilent. Several ceramic capacitors with nominal capacitance values ranging from 0.13 pF to 3 pF were used for calibration.

In the capacitance measuring unit, the components with high precision and low temperature drift were selected to ensure measurement consistency of each channel, especially the feedback capacitances and resistances. However, difference still exists among the channels. Therefore, each channel in the ECT system should be calibrated independently. Taking channel 1 in Fig. 2 as an example, the variation in the amplitude of the voltage and SNR with the capacitance value is shown in Fig. 5.

Fig. 5. Variation in amplitude of measured voltage and SNR with capacitance value.

In the measurement, the sampled data in one signal period are used for demodulation. SNR is used to compare the level of a desired signal to the level of background noise, which is defined as

$$\text{SNR} = 10 \log \frac{\sum_{l=1}^L V(l)^2}{\sum_{l=1}^L [V(l) - \bar{V}]^2}, \quad (14)$$

where $V(l)$ is the l -th measured voltage value, and $\bar{V}$ and L are the average and the total number of the measured voltage values.

By linear fitting, the capacitance value C_x in fF can be calculated by

$$C_x = 1751.7 \text{ fF}/V \cdot V_m + 15.4 \text{ fF}, \quad (15)$$

where V_m is the demodulated voltage in V . The maximum absolute error and relative error are 7.5 fF and 1.3%, respectively. Other channels were calibrated by repeating the process. It can be seen that SNR increases with the increase in capacitance, ranging from 54 dB to 80 dB when the measured capacitances are from 0.13 pF to 2.8 pF. The standard deviation is between 0.2 fF to 0.28 fF, indicating a low uncertainty of the proposed system.

B. SNR with empty-sensor

To evaluate the performance of the proposed capacitance measuring unit, a heat-resisting ECT sensor was designed, as shown in Fig. 6. The sensor consists of 12 brass electrodes of 10 cm length, which are symmetrically placed on an insulation layer of ceramic fiber paper inside a cylinder of stainless steel. The inner diameter of the cylinder is 10 cm and the height is 12 cm, for shielding.

Fig. 6. 12-electrode ECT sensor.

After calibration, the parallel-mode capacitance measuring unit is used to measure the capacitances between every two electrodes in the ECT sensor. For the 12-electrode sensor, the number of independent capacitance values is 66. The capacitance values measured by the proposed ECT system are shown in Fig. 7, ranging from 100 fF to 2.8 pF.

Fig. 7. Capacitance values measured by the proposed system.

To reduce the influence of switching oscillations caused by switching the excitation electrode from one to another, a delay time of 5 μs is used after electrode switching. If the samples in 0.6, 1 and 4 period(s) of the sampled signal are

used for demodulation, the demodulation time, T_d , is 6 μs , 10 μs and 40 μs , and the data acquisition rate, v_p , is 15150, 11111 and 3703 frames per second, respectively. SNR of the 66 capacitance values is calculated from 100 consecutive data, as shown in Fig. 8.

Fig. 8. SNR of the 66 capacitance values when samples in 0.6, 1 and 4 period(s) are used for demodulation.

If the samples in 0.6 periods are used for demodulation, the data acquisition rate is 15150 frames per second with SNR from 33 dB to 75 dB. When the samples in 4 periods are used for demodulation, the data acquisition rate drops to 3703 frames per second with SNR increased to between 40 dB and 80 dB. If samples in more periods are used for demodulation, the data acquisition rate would become lower and SNR higher. Therefore, trade-offs between the speed and SNR can be made according to a specific application.

C. Data acquisition rate

Fig. 9 shows a matrix consisting of capacitances between every two electrodes, where C_{m-n} is the capacitance value between electrodes m and n . Because $C_{m-n} = C_{n-m}$, the number of the independent capacitance values for one frame of image is $N(N-1)/2$. For a serial-mode ECT system, the capacitance values in the upper triangle can be obtained for one frame image. For a parallel-mode ECT system, the capacitance between each pair of electrodes is measured twice for one measurement period in Fig. 9, corresponding to two ECT images.

Fig. 9. Capacitance values measured by the serial and parallel mode ECT systems in one measurement period.

The data acquisition rate of a digital ECT system is determined by the excitation frequency, the number of electrodes and the capacitance measurement time, including the demodulation time and delay time after electrode switching. For a serial-mode ECT system, the data acquisition rate is

$$v_s = \frac{1}{\frac{N(N-1)}{2} \cdot (T_d + T_s)}, \quad (16)$$

where N is the electrode number, T_d is the demodulation time and T_s is the delay time after electrode switching.

For the parallel-mode ECT system, the data acquisition rate becomes

$$v_p = \frac{2}{N \cdot (T_d + T_s)}. \quad (17)$$

Therefore, the data acquisition rate of the parallel-mode ECT system is $N-1$ times of a serial-mode ECT system for an N -electrode ECT sensor. If the frequency is 100 kHz, the data acquisition rates of different number of electrodes, demodulation time and capacitance measurement modes are given in Table I.

TABLE I
COMPARISON OF DATA ACQUISITION RATES FOR DIFFERENT NUMBERS OF ELECTRODES, DEMODULATION TIMES AND SYSTEM MODES

System mode	N	Number of periods for demodulation	Time (μ s)	Delay time after electrode switching (μ s)	Data acquisition rate (frames per second)
Serial	12	4	40	5	336
		1	10	5	1010
		0.6	6	5	1377
	16	4	40	5	185
		1	10	5	555
		0.6	6	5	757
Parallel	12	4	40	5	3703
		1	10	5	11111
		0.6	6	5	15150
	16	4	40	5	2777
		1	10	5	8333
		0.6	6	5	11364

The data acquisition rate of the proposed system can be further improved by increasing the excitation frequency. Therefore, the proposed system can be applied to monitor rapidly-changing processes. The sampling frequencies of the ADCs in the proposed system are 40 MHz. It should be noted that if the sampling frequency is fixed, increasing the excitation frequency will decrease the number of samples in one period for demodulation, and hence reduce the SNR. Meanwhile, a high-performance data transmission device should be used to ensure high-speed and stable transmission.

IV. EXPERIMENTS AND RESULTS

A. Experimental setup

The proposed ECT system was used to monitor the flame generated by a Bunsen burner. Fig. 10 shows the

experimental setup, including the parallel-mode measuring unit, the heat-resisting ECT sensor, a Bunsen burner, a pulse igniter and a host computer.

Fig. 10. Experimental setup for flame monitoring.

B. Static experiment results

In the static experiment, the proposed system was used to capture the position of the flame, which was placed inside of the ECT sensor. The flame was placed at five different cross-sectional positions. The permittivity distribution was reconstructed from the measured capacitance values using the Calderon method [30], as shown in Fig. 11.

The Calderon method is a linearized method and suitable for detection of low contrast dielectrics [31]. Full-field calibration data are not required by using the Calderon method. This method is fast as no matrix inversion or iterative process is needed. It can be seen that the developed ECT system can well capture the position of flame.

C. Dynamic experiment results

In the dynamic experiment, the ECT system was used to capture the changes of the flame during the ignition process. The samples in one period of the sampled signal are used for demodulation and the data acquisition rate is 11111 frames per second. The valve of the fuel inlet was firstly opened and methane and dry air were premixed at the inlet of the burner. After ignition, a flame was generated. In some time, the flame became stable.

The images reconstructed by the Calderon method are shown in Fig. 12. The intervals of every two adjacent ECT images are 8.3 ms. When the mixed methane/air is ignited, charged particles are produced because of violent chemical reactions, resulting in larger permittivity in the reaction region.

Fig. 12 shows that the flame (red zone) expands fast after ignition and then shrinks to normal size in a short time, less than 0.2 s. After that, the position of the flame becomes stable and the relative permittivity in the flame area fluctuates in a small range. The ignition process can be clearly distinguished by the reconstructed images.

Fig. 11. Cross-sectional images of flame reconstructed by the ECT system.

Fig. 12. Cross-sectional images reconstructed by the Calderon method in the ignition process.

The variation in averaged relative permittivity with time in the ignition process is shown in Fig. 13. When the pulse ignitor is switched on, a high voltage is produced between its two electrodes and a series of electric sparks are generated with breakdown of air. The mixed methane/air is heated by the electric sparks and the flame kernel is generated and expanded. When the temperature of the flame kernel reaches the ignition point, the flame band is ignited.

In the ignition process, the electric charges in the electric sparks are transmitted to the interior zone of the ECT sensor with the flame. Then the discharge process of the pulse ignitor can be captured by the ECT system, which is reflected by the narrow peaks in Fig. 13.

To obtain direct comparison between the parallel and serial modes, the data from the serial-mode ECT were extracted from the data series of the parallel-mode rather than obtained separately. In this way, the target flame can be exactly the same for both modes. To do this, the j -th capacitance value in the serial mode was extracted from the capacitance values in the j -th row in Fig. 9, which were measured by the parallel-mode system. Then the data of one frame image in the serial mode can be obtained from the data of 11 frame images in the parallel mode. The results obtained by using the serial mode are also shown in Fig. 13.

As shown in Fig. 13, faster temporal details of the relative permittivity change can be captured by the proposed parallel-mode system. Five discharge processes of the ignitor have been captured by the parallel-mode system but only three have been captured by the serial mode system.

Compared with the serial-mode system, the parallel-mode system can provide a higher temporal resolution.

Fig. 13. Variation in averaged relative permittivity with time in the ignition process.

Taking the first two discharge processes as examples, the reconstructed images at point 1 to point 4 by using the parallel-mode and serial-mode systems are shown in Fig. 14 (a) and (b). The intervals of every two adjacent ECT images are 0.18 ms and 0.99 ms for the parallel-mode and serial-mode systems, respectively.

From Fig. 14 (a), we can see that both the parallel-mode and serial-mode system can capture the first discharge process. However, the averaged relative permittivity at point 2 is much lower than that at point 1. This means that only part of the fast process is captured by using the serial mode. In

addition, the time at point 2 is later than the time at point 1, which means the response speed of the parallel-mode system is higher than the serial-mode system. We can obtain similar conclusions in the third and fifth discharge processes.

Fig. 14. Reconstructed images by using the parallel-mode and serial-mode systems. (a) ECT images at point 1 and point 2. (b) ECT images at point 3 and point 4.

From Fig. 14 (b), we can see that the second discharge process of the ignitor has weaker effect on the ECT image captured by the serial-mode system. It means that the serial-mode system can hardly capture this process but the parallel-mode system can.

In summary, the proposed parallel-mode system is of a higher data acquisition rate and a faster response than the serial mode system. It can be used to monitor the ignition process of plasma, which is beneficial to fundamental combustion studies.

The actual limitation of the system is that $N-1$ channels of

capacitance measurement are used rather than one channel. With the increase of N , the complexity of the circuits increases too. In addition, difference among channels should be considered before use.

V. CONCLUSIONS

In this paper, a parallel-mode high-performance ECT system is presented by combining the digital recursive demodulation and parallel-mode capacitance measuring methods, which was used for monitoring of a flame. The data acquisition rate of the parallel-mode system is $N-1$ times of the serial-mode ECT system with the same excitation frequency and the same N -electrode sensor. With the excitation frequency of 100 kHz, 0.6 periods of data for signal demodulation, and a delay time of 5 μ s after excitation electrode switching, the demodulation time is 6 μ s, the data acquisition rate is 15150 frames per second with SNR from 33 dB to 75 dB, confirming that the proposed ECT system can provide a high temporal resolution for rapidly-changing processes. The proposed system was used to capture the ignition process of a flame generated by a Bunsen burner. Experimental results show that the proposed system can show the position and the ignition process of the flame. The high temporal resolution of the proposed system is beneficial to dynamic combustion studies.

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