Progress on Capacitive Sensing for Real-Time Process Tomography

S. Chowdhury, C. Gunes, D. Ospina-Acero, R. K. Rasel, F. L. Teixeira
ElectroScience Laboratory, The Ohio State University
Columbus, OH 43212 USA
email: teixeira.5@osu.edu

Q. M. Marashdeh
Tech4Imaging LLC
Columbus, OH 43212 USA
email: marashdeh@tech4imaging.com

***Abstract*—We report on recent progress in the development of capacitive sensors for real-time tomography of industrial processes. In particular, we describe recent developments on: (1) adaptive electrical capacitance volume tomography (AECVT) sensors based on reconfigurable synthetic electrodes, (2) multi-frequency acquisition strategies exploiting the Maxwell-Wagner-Sillars effect in multiphase flows, (3) displacement current phase tomography for imaging of fluid flows, and (4) flow velocity profiling based on electrical capacitance volume tomography (ECVT) sensors.**

I. INTRODUCTION

Electrical Capacitance Tomography (ECT) has been widely used for imaging multiphase flows in oil pipelines, fluidized beds, wet gas separators, and many other industrial applications [1]–[3]. ECT has advantages over X-ray or MRI as it is much cheaper and enables real-time imaging of the region of interest (RoI). ECT hardware comprises multi-electrode capacitance plates placed around a flow vessel, where the inter-electrode capacitances are measured to find the permittivity distribution inside the vessel. In this work we succinctly describe a number of recent developments on ECT: (1) adaptive electrical capacitance volume tomography (AECVT) sensors based on reconfigurable synthetic electrodes, (2) multi-frequency acquistion strategies exploiting the Maxwell-Wagner-Sillars effect in multiphase flows, (3) displacement current phase tomography for imaging of fluid flows, and (4) flow velocity profiling based on electrical capacitance volume tomography (ECVT) sensors.

II. RECENT DEVELOPMENTS

A. Adaptive Electrical Capacitance Volume Tomography

AECVT has been recently proposed as an ECVT augmentation that enables the electronic combination of a much larger number of small-sized individual segments to form synthetic electrodes [4], [5] while attaining given minimal area requirements as set by the SNR necessary to a particular application. Importantly, by partially overlapping the areas of each synthetic electrode, either axial or azimuthal scanning allow for a larger number of capacitance measurements. Additionally, AECVT-based electronic scanning does not incur any of the practical disadvantages associated with a physical movement of parts such as higher power consumption, low acquisition speed, and the need for high mechanical precision and reliability. Reconstruction results have shown enhanced resolution and imaging stability compared to the conventional ECVT sensing [5]. By using AECVT-enabled electronic scanning, the sensitivity of a voxel in the RoI can be more gradually varied without changing the (synthetic) electrode plate size and thus without compromising the signal-to-noise-ratio of the measurements (see Fig. 1).

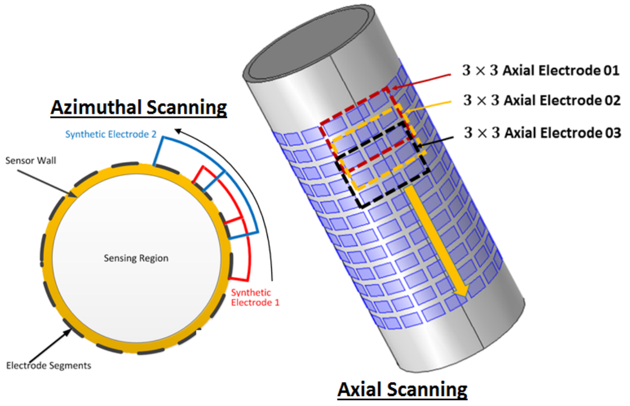

Fig. 1: Schematic idea of AECVT operation.

B. Exploiting the MWS Effect in ECT

Conventionally, sensors used for flow imaging can only sense a change in signal is response to a single property being monitored (say, permittivity). This has restricted application of process monitoring techniques to two-phase flows only. For three-phase applications, users need to employ different sensors simultaneously [6], [7]. A new approach for multi-phase flow monitoring based on the use of an pre-existing ECT hardware system has been recently proposed based on the addition of extra information enabled by multi-frequency excitations [8], [9] and the exploitation of the Maxwell-Wagner-Sillars (MWS) effect on dieletric mixtures. The MWS effect is a consequence of surface migration polarization at the interface between materials when at least one of them is conducting [10]. Such multiphase system (mixture) can be composed of air, water (conducting phase), and oil, for example. Although typically each phase in the multi-phase mixture has a near-uniform dielectric constant over the quasi-static frequency range, a mixture will exhibit more pronounced

978-1-5386-7105-4/18/$31.00 ©2018 IEEE

changes in frequency response due to the MWS effect. The MWS effect is more pronounced for mixtures with conductive dispersed phases in a non-conductive continuous phase, and allows for the continuous real-time monitoring of multi-phase flows containing conductive phases [9].

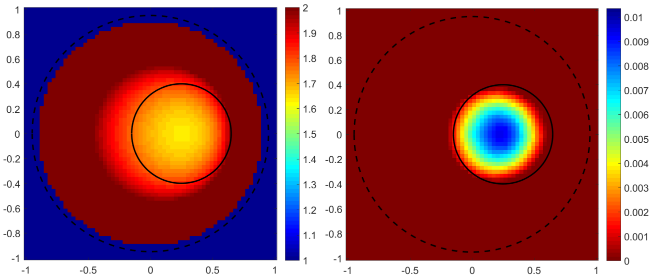

Fig. 2: Columnar air flow in water background (RoI of 1 m radius). Left: ECT reconstruction result with blurring caused by high background permittivity. Right: DCPT reconstruction result (for 300 kHz as frequency of operation)

.

C. Displacement Current Volume Tomography

In contrast to ECT, Displacement Current Phase Tomography (DCPT) utilizes directly the *phase* information of the displacement current in the electroquasistatic (EQS) regime to provide information about the distribution of the loss factor (or loss tangent) within the RoI [11]. An attractive feature of DCPT is that the relation between the measured phase and the loss factor inside the RoI has a more extended linear range than the relationship between the measured capacitances and the permittivity distribution in ECT. This characteristic is especially useful in reconstructing multiphase flows where the continuous phase is water (which is especially challenging for ECT). Since DCPT can be implemented using the same hardware that is used for ECT, both technologies can be easily employed alongside to provide additional data for reconstruction purposes [11]. In addition, DCPT does not require any electrical contact with the RoI (in contrast to, for example, impedance tomography). Fig. 2 shows a comparison of ECT and DCPT for the imaging (by the use of the iterative Landweber method for reconstruction) of a columnar flow of an air column in a background composed of tap water ($\epsilon_r = 80$ and $\sigma = 5.5 \times 10^{-6}$ S/m). The figure shows that the ECT result is degraded by the significant nonlinear effect caused by the high permittivity contrast, which shifts and blurs the image. DCPT, on the other hand, produces a much sharper image.

D. Flow Velocity Profiling

ECT has been also applied for the determination of flow velocity. This can be done by placing two independent sensors around the vessel and cross-correlating the 2D images found from each of them [12]. However, this approach has important drawbacks [13]. Recently, a new method was proposed for velocity profiling of multiphase flows that aims to overcome the drawbacks of the conventional approach. The new method is still based on ECVT, but instead of cross-correlation, it utilizes the capacitive sensor sensitivity gradient to extract velocity information [14]. The sensitivity gradient exploited in this approach is a linear approximation that maps displacements of permittivity distribution to a change in the measured capacitance between two successive frames (measurement acquisitions) [15]. This constitutes a new forward problem based on which the displacement profile can be determined using conventional reconstruction techniques already utilized in ECVT (e.g., Linear Back Projection (LBP), Landweber iteration, etc.). Once the displacement profile is found, the velocity profile can be obtained by simply incorporating the frame rate. This novel mapping not only obviates the need for image cross-correlations but also is fully compatible with existing ECVT sensor and image reconstruction algorithms [15].

REFERENCES

[1] W. Warsito and L.-S. Fan, “Dynamics of spiral bubble plume motion in the entrance region of bubble columns and three-phase fluidized beds using 3D ECT,” *Chem. Eng. Sci.*, vol. 60, no. 22, pp. 6073–6084, Nov. 2005.

[2] S. Liu, Q. Chen, H. G. Wang *et al.*, “Electrical capacitance tomography for gas-solids flow measurement for circulating fluidized beds,” *Flow Meas. Instrum.*, vol. 16, no. 3, pp. 135–144, Jun. 2005.

[3] Q. M. Marashdeh, F. L. Teixeira, and L.-S. Fan, “Electrical capacitance tomography,” in *Industrial Tomography: Systems and Applications*, M. Wang, Ed., 1st ed. Cambridge, UK: Woodhead/Elsevier, 2015, ch. 1, pp. 3–21.

[4] Q. M. Marashdeh, F. L. Teixeira, and L.-S. Fan, “Adaptive electrical capacitance volume tomography,” *IEEE Sensors J.*, vol. 14, pp. 1253–1259, Apr. 2014.

[5] Z. Zeeshan, F. L. Teixeira, and Q. M. Marashdeh, “Sensitivity map computation in adaptive electrical capacitance volume tomography with multielectrode excitations,” *Electron. Lett.*, vol. 51, no. 4, pp. 334–335, Feb. 2015.

[6] Q. M. Marashdeh, W. Warsito, L.-S. Fan, and F. L. Teixeira, “A multimodal tomography system based on ECT sensors,” *IEEE Sensors J.*, vol. 7, pp. 426–433, Apr. 2007.

[7] Q. M. Marashdeh, W. Warsito, L.-S. Fan, and F. L. Teixeira, “Dual imaging modality of granular flow based on ECT sensors,” *Granular Matter*, vol. 10, no. 2, pp. 75–80, Jan. 2008.

[8] R. K. Rasel, C. E. Zuccarelli, Q. M. Marashdeh, L.-S. Fan, and F. L. Teixeira, “Towards multiphase flow decomposition based on electrical capacitance tomography sensors,” *IEEE Sensors J.*, vol. 17, pp. 8027-8036, 2017.

[9] R. K. Rasel, C. Gunes, Q. M. Marashdeh, and F. L. Teixeira, “Exploiting the Maxwell-Wagner-Sillars effect for displacement-current phase tomography of two-phase flows,” *IEEE Sensors J.*, vol. 17, pp. 7317-7324, 2017.

[10] P. Becher, “Dielectric Properties of Emulsions and Related Systems,” *Encyclopedia of Emulsion Technology*, vol. 1. New York: M. Dekker, 1983.

[11] C. Gunes, Q. M. Marashdeh, and F. L. Teixeira, “A comparison between Electrical Capacitance Tomography and Displacement-Current Phase Tomography,” *IEEE Sensors J.*, vol. 17, pp. 8037-8046, 2017.

[12] W. Warsito and L.-S. Fan, “3D-ECT velocimetry for flow structure quantification of gas-liquid-solid fluidized beds,” *Can. J. Chem. Eng.*, vol. 81, no. 4, pp. 875–884, Aug. 2003.

[13] W. Q. Yang, “Design of electrical capacitance tomography sensors,” *Meas. Sci. Technol.*, vol. 21, no. 4, pp. 042001-1–13, Apr. 2010.

[14] Q. M. Marashdeh and F. L. Teixeira, “Sensitivity matrix calculation for fast 3-D electrical capacitance tomography (ECT) of flow systems,” *IEEE Trans. Magn.*, vol. 40, pp. 1204–1207, Mar. 2004.

[15] S. Chowdhury, Q. M. Marashdeh, and F. L. Teixeira, , “Velocity profiling of multiphase flows using capacitive sensor sensitivity gradient,” *IEEE Sensors J.*, vol. 16, pp. 8365-8373, 2016.