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Acousto-capacitive tomography of liquid multiphase systems

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ABSTRACT

This paper discusses a tomographic approach focusing on ultrasonic measurements to monitor liquid multiphase mixtures. Separately a capacitive tomography low-cost setup is regarded. Both sensor arrays aim for the localization of variable phase boundaries and the physical characterisation of spatially distributed phases. Focusing on a real time processing, a reduced number of transducers in combination with a fast linear modelling and direct image reconstruction methods are used. Experimental results of a layered 3-phase-system validate the potential and limits of physical resolution of both approaches. Finally, the prospectively intended data fusion of both approaches is discussed.

1. Introduction

In-process control, e.g. of liquid reactions in chemical industry, a single point inspection is adequate as long as process uniformity can be assumed [1]. However, local deviations, gradients, inhomogeneities or hotspots within the process medium cannot be detected adequately. Thus, the need of information describing the tempo-spatial distribution of medium related process parameters becomes progressively important in order to control also sophisticated processes [2]. Such an applicable measurement technique needs to fulfil different demands. On the one hand dissimilar physical properties must be mapped sufficiently. Moreover, larger process volumes must be probed with adequate spatial and temporal resolution. Not least, the sensing system should be robust and cost efficient.

The spectrum of tomographic systems available – depending on the application, the resolution and also the costs – varies from the electrical impedance [3] and capacitive [4], the electromagnetic [5] and optical, the magnet resonance tomography to the ultrasonic spectroscopy [6] and ultrasonic tomography [7,7a]. The authors' work focuses on the tomographic approach with ultrasonic waves and distributed capacitance measurements. Due to their non-destructive nature, easy handling, continuous and fast operation both techniques represent an advantageous solution for inline-process monitoring especially in case of multiphase systems. Although several contributions on ultrasonic and capacitive process tomography already exist [8], they are limited to imaging applications without medium characterization, only. Current applications concentrate on the interface detection of flowing media [9], simulation studies on imaging of cylindrical volumes by ultrasonic arrays [10] or represent cost intensive high resolution devices for medical applications [11]. An industrial-suited low-cost measurement device for the characterization of multi-layers with different liquid/liquid and/or liquid/solid interfaces in a larger process volume presently does not exist to the authors' knowledge.

In this context, the contribution discusses the possibilities of characterizing liquid multiphase media by the non-invasive approaches of separate acoustic and capacitive sensor arrays (Fig. 1). In detail, the analysis concentrates on the real time monitoring of a liquid multiphase flow within a pipe of 100 mm diameter and providing >25 data sets per second. The acquired data are used to characterize the different phases and to localize the variable phase boundaries. Here, the combination of acoustic and capacitive measurements [12,13] can provide an enhanced data basis to afford the extraction of the interesting process values. Fundamental research on data fusion of acoustic and capacitive data can be found in [14]. The work presented here especially investigates the performance of a low cost approach based on the use of commercial integrated electronics [15–17]. Both systems are evaluated separately with regard to the task of real time tomographic monitoring, while aspects of the data fusion are not explicitly handled here.

2. Model

The non-invasive approach uses an acoustic and a capacitive sensor array in which elements are distributed along the circumference of a pipe to monitor and characterize liquid mixtures and multiphase flow (Fig. 1). Whereas the acoustic probe is applicable on a variety of different pipe materials, the capacitive probe can be

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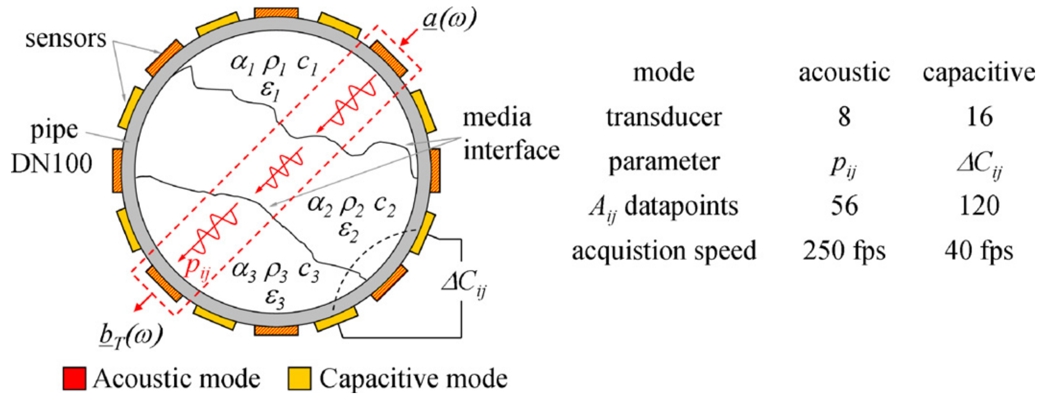

Fig. 1. Cross-section of a process pipe (DN100) with array of acoustic (8 ultrasonic transducer) and capacitive (16 electrodes) sensors placed on the pipe wall: d – mean phase dimension, ρ – density, c – sound velocity, ε – permittivity, α – adsorption, ΔC_{ij} – capacitive variation, r – position vector, p_{ij} – pressure, $a(\omega)$ – transmitted signal, $b_T(\omega)$ – received signal; with representative illustration of one transmission line between transducers i and j.

used for non conducting materials, only. Based on the propagation of a pressure wave p_{ij} with continuous ($f = 2.25$ MHz, $\omega = 2\pi f$) or transient ($f = 2.25$ MHz modulated differential gauss pulse $g(t)$ with $f_0 = 200$ kHz bandwidth and normalized amplitude $\hat{a} = 1$) excitation (1) and (2a), the information on the distribution of the sound velocity c and the ultrasonic attenuation α within the media between transmitter i and receiver j along distance r can be gained.

$$g(t) = -2\pi^2 f_0^2 \left(t - \frac{1}{f_0}\right) \hat{a} \cdot e^{-\pi^2 {f_0}^2 (t-(1/f_0))^2} \tag{1}$$

The change of the electrostatic partial capacitance ΔC_{kl} of the electrodes k and l with potentials φ_k and φ_l delivers an equivalent to the distribution of the permittivity $\varepsilon(r)$ in the process volume, which influences the electrostatic field E (2b).

$$p_{ij} = p_0 \cdot e^{j\omega(t-(r/c))} e^{-\alpha \cdot r} \tag{2a}$$

$$\Delta C_{kl} = \frac{\oiint_A \varepsilon(r) \vec{E} dA}{\varphi_l - \varphi_k} \tag{2b}$$

The presented investigations concentrate on the characterization of 3 horizontally layered flowing media with irregular interfaces. Favouring a real time processing, a reduced number of transducers (acoustic: 8, capacitive: 16, Fig. 1) in combination with fast direct reconstruction algorithms are used. Simulations of the electrostatic field distribution and sound propagation in liquid media with finite element models are used as data basis for theoretical investigations and parameter studies. The analysis of simulation data is useful because the multiple scattering and the mode conversion can be identified, neglecting clutter and experimental effects. The verification is carried out on an experimental rig for inline-analysis of flowing liquids up to a pipe diameter of 100 mm.

3. Acoustic mode

The diversity of probing methods with ultrasonic arrays vary from beam shaping, focusing and pivoting techniques with impulse echo or common source measurements to sampling phased array techniques [18] with full matrix capture – used here. Most of the tomographic algorithms [19], which are applied on those data and are used in non-destructive evaluation, scanning or medical imaging [11], deliver an intensity image of the prospected volume or two dimensional volume slice based on a priori knowledge of the media. The media characterization itself for analytical purposes is not implemented. Moreover, the forward algorithm cannot be applied on full matrix data in real time. Instead, some simplifications are made here favouring a real time imaging of the volume slice. The full wave algorithms are mostly neglected due to processing time.

3.1. Clamp-on ultrasonic tomography and full information matrix

The liquid analysis with ultrasonic waves is an advantageous measurement approach due to its non-invasive nature, easy handling and fast operation. The complete information of an unknown liquid medium is contained within the scattered, reflected or transmitted pressure waves. Typically, density, sound velocity, elasticity or temperature along the corresponding sound path can be determined [2]. Additionally, the effective acoustic attenuation can provide information on dispersive fractions [6]. Using an array of transducers with equivalent frequency bandwidth and sensitivity an increase in spatial resolution can be obtained by the superposition and migration of different transmission paths.

The aim is the tomographic monitoring of a cylindrical cross section of a pipe. The probe array consists of a number N of clamp-on ultrasonic transducers which are placed at the outside of the pipe. According to the number of transducers $N^*(N-1)$ unidirectional transmission paths occur. The data acquisition is done without focusing of the ultrasonic array to probe the pipe volume. Instead, the full matrix (Table 1) of ultrasonic transmit–receive data is measured by switching the transmitter from transducer 1 to N and measuring the remaining $N-1$ receive channels [18,20,21]. This data acquisition is carried out by sequential recording of the transmission signals regarding the decay time of multiple reflections t_A. The time signals for each pair of transducers form the information matrix A_{ij} [21]. Here the impulse echo signals A_{ii} are neglected. The sound velocity c, the divergence of the acoustic field and the damping α mainly influence the acquisition speed with direct proportionality. Exemplarily, when assuming a pipe cross section of diameter $d = 100$ mm filled with homogeneous water ($c = 1480$ m/s at 20 °C) and a decay time t_A where no multiple echos are detectable

Table 1
Full information matrix A_{ij} for transmission mode with $N = 8$ transducers: note the pulse echo data A_{ii} is not recorded and further the values used for linear transmission modelling (see Section 3.3) are marked bold.

N	1	2	3	4	5	6	7	9
1		A_{12}	A_{13}	A_{14}	$\mathbf{A_{15}}$	A_{16}	A_{17}	A_{18}
2	A_{21}		A_{23}	A_{24}	A_{25}	$\mathbf{A_{26}}$	A_{27}	A_{28}
3	A_{31}	A_{32}		A_{34}	A_{35}	A_{36}	$\mathbf{A_{37}}$	A_{38}
4	A_{41}	A_{42}	A_{43}		A_{45}	A_{46}	A_{47}	$\mathbf{A_{48}}$
5	$\mathbf{A_{51}}$	A_{52}	A_{53}	A_{54}		A_{56}	A_{57}	A_{58}
6	A_{61}	$\mathbf{A_{62}}$	A_{63}	A_{64}	A_{65}		A_{67}	A_{68}
7	A_{71}	A_{72}	$\mathbf{A_{73}}$	A_{74}	A_{75}	A_{76}		A_{77}
8	A_{81}	A_{82}	A_{83}	$\mathbf{A_{84}}$	A_{85}	A_{86}	A_{87}	