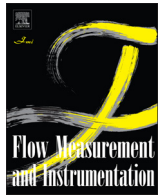




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A real-time ultrasound process tomography system using a reflection-mode reconstruction technique

Sascha Langener^{a,*}, Michael Vogt^b, Helmut Ermert^b, Thomas Musch^a

^a Institute of Electronic Circuits, Ruhr-University Bochum, 44780 Bochum, Germany

^b High Frequency Engineering Research Group, Ruhr-University Bochum, 44780 Bochum, Germany

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ABSTRACT

The measurement of volume fractions of different components in multiphase flows is of great interest in many industrial applications. Ultrasound process tomography is especially well-suited for the differentiation of gaseous and liquid phases. This paper presents a measurement system, which was developed for real-time ultrasound process tomography, utilizing a ring of 32 ultrasound transducers on a measurement pipe. Simulations and measurements were conducted, and a reflection-mode reconstruction technique was used to obtain the system's point spread function and examine the performance on inhomogeneous configurations of water containing multiple gaseous objects. Furthermore, the possibility of increasing the measurement rate by reducing the number of excitations and its effects on the quality of the reconstructed images is investigated.

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1. Introduction

In many industrial applications, where multiphase flows are involved, knowledge of the volume fractions of the different phases is greatly desired to control and optimize production processes [1]. Due to its capability to give informations about the spatial distribution of phases, process tomography is of particular interest. A number of measurement concepts exist using ionizing radiation, electrical fields, microwaves, and ultrasonic waves. Ultrasound is sensitive to mechanical material properties like density. For this reason, ultrasound-based measurement techniques are well-suited for the differentiation of liquid and gaseous phases. Especially the large reflectivity coefficient of more than 99% [2] at liquid/gaseous interfaces makes it suitable for measurements on two-phase media. Compared to radiation based methods, ultrasound tomography has the advantage of low costs and negligible safety issues. Furthermore, its small wavelength allows for a very good spatial resolution compared to electrical tomography. A disadvantage of ultrasound is the low speed of sound, resulting in large measurement times. These put constraints on the allowed changing speed of the flow on which the measurements are to be conducted [3].

Numerous approaches for ultrasound process tomography of two-phase media have been reported (e.g. [3–7]), where typically a

ring of ultrasound transducers along the circumference of a cross-section of a measurement pipe containing the multiphase flow is used. All, or a subset, of the transducers is sequentially used as transmitters to insonify the cross-section from multiple directions. The transducers are also used as receivers of the transmitted and scattered ultrasound waves. Depending on the parameter that is to be reconstructed, some of the existing techniques are based on the evaluation of transmitted waves [4,5], others use echo measurements in the so-called reflection-mode [6,7]. Furthermore, combinations can be used to improve the quality of reconstruction results, as suggested in [3] for example. To achieve a good spatial resolution, the transmitters are excited with broadband pulses. This requires comparably large power to be delivered to the ultrasound transducers to achieve a large dynamic range of the measurement system. This is necessary, as the amplitude of reflected ultrasound waves varies significantly for inhomogeneous media. In the case of large, gaseous objects, large amplitudes occur, what also strongly depends on the shape of the interface. In the case of multiple objects smaller than the wavelength, a significant attenuation by scattering of the waves occurs.

In this contribution, an ultrasound tomography system, which was developed on the basis of previous work [8], is presented in detail. It aims at the measurement of the amplitude and the *time of flight* (TOF) of ultrasound waves, transmitted through or scattered in a cross-section of a measurement pipe. This is achieved, by sequential excitation of individual transducers, while all of the transducers are used as receivers. For comparison to results under idealized conditions, simulations of the measurement system were also conducted. A reflection-mode reconstruction technique was

* Corresponding author.

E-mail address: sascha.langener@est.ruhr-universitaet-bochum.de (S. Langener).

used to obtain images of the spatial distribution of two-phase configurations in the cross-section. The measurement system and the reconstruction technique are characterized by an evaluation of the *point spread function* (PSF) and also by examination of reconstruction results for two-phase configurations.

2. Measurement system and simulation technique

2.1. Measurement system

Fig. 1 shows a photograph of the measurement system, which was developed for investigations on multiphase flows. A set of 32 ultrasound transducers is attached along the circumference of the measurement pipe (53 mm inner diameter, 4 mm wall thickness) made of polyvinylidene fluoride (PVDF). PVDF was chosen because it has a good chemical resistance and an acoustic impedance similar to those of liquids [9]. This results in a small mismatch and reduces multiple reflections inside the pipe's wall. Additionally, PVDF has a large attenuation factor (13.4 dB/cm/MHz) [9] what dampens the multiply reflected waves inside the wall.

Fig. 2 shows a CAD-Model of the single element ultrasound transducer developed for the measurement system. For the electromechanical conversion a ceramic piezoelectric element (lead zirconate titanate, PZT) with a resonance frequency of 520 kHz is used. A wavelength of approximately 2.8 mm in water is given at the resonance frequency, chosen as a compromise between a good spatial resolution and a sufficiently small attenuation of the ultrasound waves. A strip of borosilicate glass is placed in front of the piezoelement as a matching layer, in order to improve the transmission of ultrasound waves between the ceramic and the pipe's wall and also increase the transducer's bandwidth. At the rear side, a so-called backing is placed, consisting of tungsten-loaded epoxy (45%vol.) in an aluminum-case. The backing increases the bandwidth of the transducer to $B_{Td} = 460$ kHz. The aperture sizes of the transducer are 21 mm in axial direction, i.e. along the pipe's axis, and 1 mm in lateral direction, i.e. perpendicular to the axis. The axial dimension is considerably larger than the wavelength in order to obtain a narrow beam pattern in the axial direction, concentrating the ultrasound waves to the cross-section of interest. The lateral extend of the aperture, as it is smaller than the wavelength results in a diverging beam pattern of the transducer. This fan-shaped beam pattern allows for the in-sonification of a large area of the cross-section with each excitation. The narrow shape of the transducers is furthermore favorable, as it allows for a high number of transducers to be attached to the circumference of the measurement pipe.

As a drawback of the small area of the aperture, the electrical input impedance of the transducer is mainly capacitive with a small real part. Therefore, the transducers have to be driven with large voltages, especially when broadband pulses are used. The transmit signals are generated by means of *Digital-to-Analog-Converters* (DACs), as shown in the schematic of the implemented excitation circuit in Fig. 3. The differential output signal of the DAC is amplified by a fully-differential operational amplifier, which drives a *power amplifier* (PA) in push-pull configuration. Two MOSFET-transistors, utilized as controlled current sources, are driving a transformer with center tapped primary winding and a turns ratio of 1:10. This configuration allows for an amplitude $\overline{V_{out}} = 500$ V at the transducer, with only a single-sided supply voltage $V_{CC} = 50$ V.

Because every transducer is intended for transmission and also for reception of ultrasound waves, sensitive measurement electronics are also connected to each transducer. During excitation, they have to be separated from the power amplifier. This is achieved by means of an amplitude *limiter*, realized by a diode-

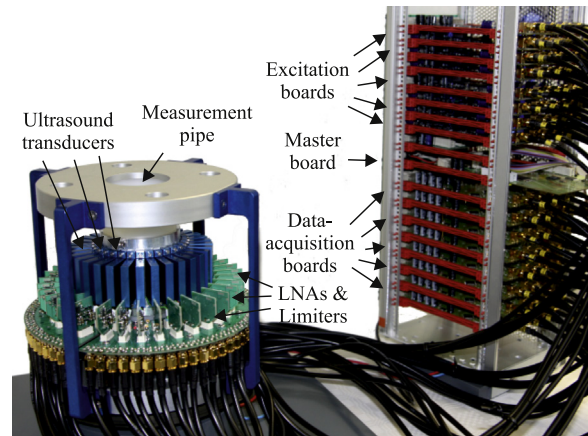


Fig. 1. Photograph of the measurement pipe and the electronics of the realized measurement system.

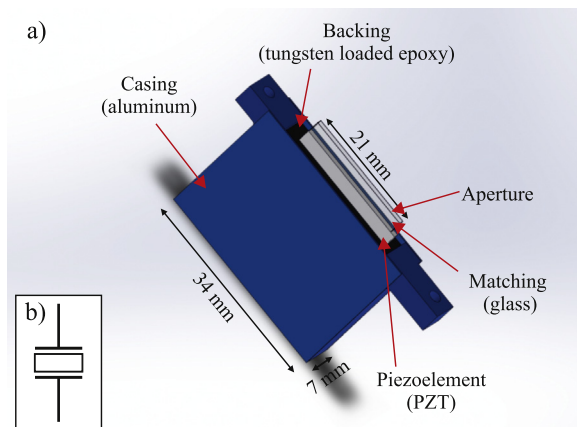


Fig. 2. Ultrasound transducer: (a) CAD-model and (b) graphical symbol.

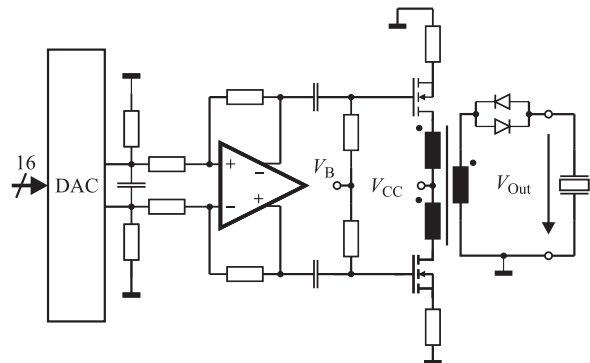


Fig. 3. Schematic of the implemented excitation circuit.

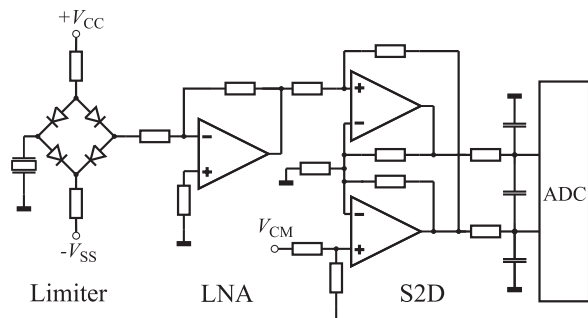


Fig. 4. Schematic of the implemented measurement and data-acquisition circuit.

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