Sound velocity measurements in fluids using echo signals from scattering particles

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A novel approach for measuring the speed of sound in fluids with scattering particles is presented. Potential fields of application for sound velocity measurements in fluids are process control, environmental measurement technology and medicine, where sound velocity can be used as an indicator of temperature, concentration or mass density. Similar to the pulsed Doppler application, the method also works non-invasively and uses the echo signals from scattering particles suspended in the fluid. The basic idea is that the ultrasonic time of flight to the focus position *z* depends on the speed of sound *c* in a well-defined way. The time of flight to the focus can be extracted from the echo signals, because the stray echo is strongest for the scattering particles being located in the sound focus and can thus be used to determine the speed of sound. Results are shown for different homogeneous fluids with sound velocities between 1116 m/s (ethanol, 50 °C) and 2740 m/s (eutectic GaInSn). Measurements have shown that a statistical measurement uncertainty of about 0,1 % was achieved with the underlying set-up. Further results of recent measurements in water having a temperature gradient show that the method is even capable of measuring the sound velocity with local resolution.

Keywords: speed of sound, material characterisation, scattering particles, annular array

1 INTRODUCTION

Ultrasonic measurements are widely used for flow measurements in scientific and industrial applications. Their advantages primarily lie in measurements in opaque fluids, where optical methods such as PIV cannot be applied.

A large number of ultrasonic measurements are based on the Doppler method, which analyses the stray echoes originating from scattering particles suspended in the fluid. While the current method is comparable to Doppler methods in that it uses the same echo signals, it is, however, not intended to measuring mass transport, but rather the speed of sound. By that way, it enables access to an additional measuring variable that is otherwise measurable solely with invasive methods such as bringing reflectors of known position into the fluid and measuring the time of flight between these reflectors. In a way, the method thus addresses to the result of mass transport rather than the process itself.

An interesting application from the point of view of fluid mechanics, is the measurement of concentration of a two-phase metal melt with two constituents having different sound velocities

2 FUNCTIONAL PRINCIPLE

2.1 Basic idea

The functional principle is based on the fact that the focus position (and related to that the time of flight to the ultrasonic focus – the variable that is accessible by measurement) depends on the speed of sound in the medium and on the transducer.

This concept is visualised in Fig. 1, where the simulated sound fields of a focusing transducer in the fluids ethanol, water and eutectic GaInSn are plotted versus the corresponding measurements of the echo signal amplitudes. For clarity, the measured times of flight were converted into the corresponding focus distance to the transducer using the known sound velocities of fluid and the acoustic lens that the transducer was equipped with for focusing purposes.

2.2 Theoretical calibration curve for a circular piston transducer

The basic idea can be understood analytically for a circular piston transducer. For this kind of transducer, the focus position is given by

$$z_{\mathrm{foc}} = \frac{D^2}{4 \cdot \lambda} = \frac{D^2 \cdot f_{\mathrm{US}}}{4 \cdot c} \tag{1}$$

with the transducer diameter *D,* the wavelength λ the ultrasonic frequency f_{US} and the sound velocity *c*. Considering that

$$z_{\mathrm{foc}} = \frac{1}{2} \cdot c\, t_{\mathrm{SFM}} \tag{2}$$

with the two-way time of flight t_{SFM} to the sound field maximum, this leads to the theoretical calibration curve

$$c = \sqrt{\frac{D^2 \cdot f_{\mathrm{US}}}{2 \cdot t_{\mathrm{SFM}}}} \tag{3}$$

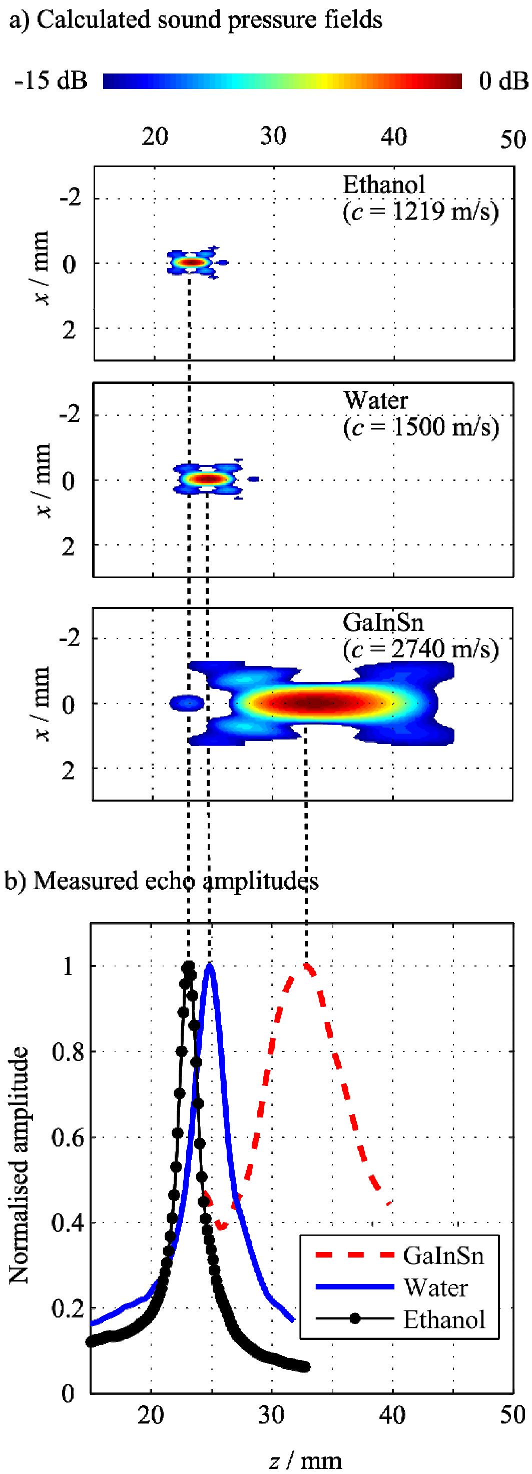

Figure 1: The maximum position of the echo signal amplitude curve indicates the position of the sound field maximum in the fluid. (a) Sound field simulations for different propagation media. (b) Time-averaged echo signal amplitude using the focusing ultrasonic transducer in media with different sound velocities. The measured times of flight have been converted into the corresponding measurement depth for easier comparison between measurements and simulations. Figure source: [1].

of the circular piston transducer. Since for most transducer geometries, analytical solutions are not available, numerical simulations were used, here.

3 DESCRIPTION OF EXPERIMENTS

Two different experiments were carried out: (i) an experiment with a focusing transducer equipped with a ceramic lens, and (ii) experiments with a sparse annular having six active elements – an annular array with ring elements of equal size and passive gaps between the elements.

(i) The measurements with the focusing transducer equipped with a lens were done in media with sound velocities between 1116 m/s (ethanol, 50 °C) and 2740 m/s (eutectic GaInSn) listed in Tab. 1.

Table 1: Fluids used in the measurements with the focusing transducer equipped with a lens.

Fluid	Temp./ °C.	*c*/(m/s)
Ethanol 95%	50	1116
Ethanol 95%	36	1169
Ethanol 95%	20.7	1219
Ethanol 70%	23.9	1377
Tap water	6	1431
Ethanol 50%	25.8	1499
Tap water	30	1509
Tap water	60	1551
Glycerine 39%	23.8	1685
Glycerine 59%	23.8	1785
Glycerine 85%	22.3	1879
GaInSn	20	2740

(ii) The measurements with the sparse annular array were carried out in ethanol and water. To change the focus position by signal processing, which is an important premise for achieving a local resolution of the sound velocity, the receiving signals of the different array elements were time-shifted to compensate the differing path lengths between the respective array element and the focus (focusing in receive mode).

Measuring the band-pass filtered high frequency signals and averaging their envelopes (absolute values of the Hilbert transformation) over a multitude of measurements finally led to the curves shown in Fig. 1b. Further details about the experimental-setup and the simulation method can be found in [1-2].

3 MEASUREMENT RESULTS

The experiment (i) using the focusing transducer equipped with a ceramic lens primarily confirms the underlying concept and experimentally proves its validity for a sound velocity range between 1116 m/s and 2740 m/s. The results are shown in Fig. 2. Note that Fig. 2 can be considered to be a calibration curve, which comprises the characteristics of the specific transducer. The deviation between measured and simulated curves in Fig. 2 is about 3 %.

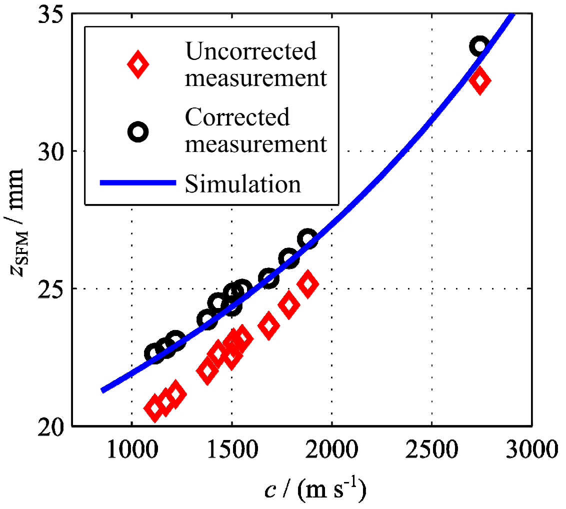

Figure 2: Calibration curve for the focusing transducer equipped with a lens. The correction considers the different speeds of sound in the ultrasonic lens and the propagation medium. Figure source: [1].

In a more detailed measurement described in [1], water of different temperatures was used to precisely adjust the sound velocity and test the statistical uncertainty of the method. A statistical deviation between measurements and fit curve for that method of about 1,41 m/s (0,1 %) was found. This means that the largest part of the 3 % uncertainty consist of systematic uncertainties such as an uncertainty in the knowledge of the true sound velocity and the parameters for the lens material and geometry.

Experiment (ii) using the annular array proofs that the calibration curves depend on the sound velocity of the propagation medium. Two calibration curves of the annular array are shown for $c = 1200$ m/s and 1430 m/s. The measurements were done in *focusing in receive* mode.

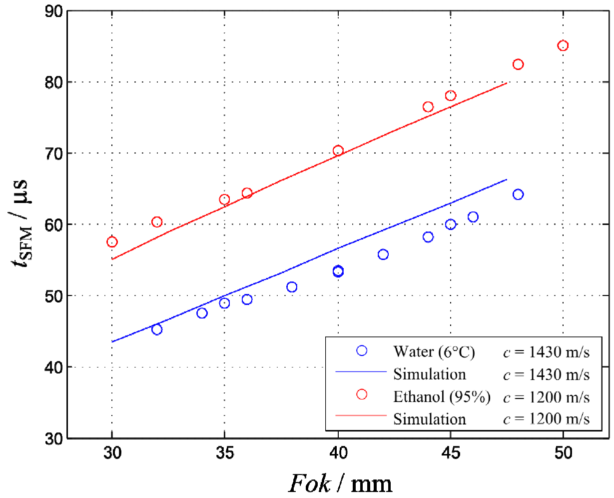

Figure 3: Calibration curves for the sparse annular array in ethanol (*c* = 1200 m/s) and water (*c* = 1430 m/s).

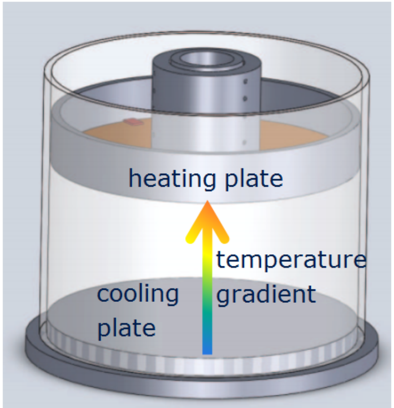

Figure 4: Set-up for generating a temperature gradient. The cooling plate needs to be on the bottom to avoid convection.

4 ONGOING RESEARCH

Current research concentrates on the following aspects:

- reducing the statistical uncertainty of the determination of the focus position,
- measurement of the local distribution of sound velocity, and
- influence of sound propagation on focus determination.

The reduction of the statistical uncertainty for the determination of the focus position is mainly done by focusing in *send* and *receive mode*. This means that both the emitted ultrasonic wave and the receiving signals are focused. This makes the ultrasonic focus smaller than for focusing in just one direction and contributes to a larger signal to noise ratio.

Measurement of the locally and temporarily resolved sound velocity is one of the main topics for future applications in flow research. Up-to-date measurement results will be shown for measurements in water having a temperature gradient between 10 °C and 60 °C, which is equivalent to a sound velocity gradient of between 1450 and 1550 m/s. The gradient generation is done with the set-up shown in Fig. 4. Recent measurements have verified that the method is capable of achieving a local resolution for the sound velocity. However, a dependence of curvature of the piezoelectric element on the fluid temperature was found, which affects the focusing behaviour of the transducer and needs to be suppressed (or studied in more detailed) before final results can be given.

Further attention is also being paid to the influence of the attenuation of the propagation medium on the measurement results. In fluids with high attenuation, the measured ultrasonic focus (defined as the location exhibiting the highest sound pressure) tends to be located closer to the transducer than the locating with maximum constructive interference.

5 SUMMARY

The presentation introduces a novel approach for non-invasive sound velocity measurements in fluids that is based on the echo signals of scattering particles suspended in the fluid. Experimental proof is shown for fluids covering the wide range of sound velocity between 1116 and 2740 m/s.

The possibility to change the focus depth via time-shifted superposition of the echo signals belonging to the elements of an annular array allows to measure the sound velocity with local resolution without the need for any movement of the transducer. First sound velocity gradients measured in water exhibiting a temperature gradient are shown, and different aspects on improving the method and making it a useful tool for flow research are discussed.

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