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Measurements of streams agitated by fluid loaded SAW-devices using a volumetric 3-component measurement technique (V3V)

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Abstract

Utilizing surface acoustic waves (SAW) to induce tailored fluid motion via the acoustic streaming requires detailed knowledge about the acoustic bulk wave excitation. For the first time, the Defocus Digital Particle Image Velocimetry is used to measure the fluid motion originating from a fluid loaded SAW-device. With this flow measurement technique, the acoustic streaming-induced fluid motion can be observed volumetrically, which is attractive not only for application, but also for simulation in order to gain deeper insights regarding three-dimensional acoustic effects.

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Keywords: acoustic streaming, PIV, acoustic source, SAW, V3V, DDPIV

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1. Introduction

Homogenisation of different fluids in a test tube is one of the main tasks for laboratories using autosamplers. Mostly, this is done by employing a magnetic stirrer that spins small fleas immersed in the solutions. The injection and the removal of the fleas is a time-consuming process. A promising alternative is the usage of a surface acoustic wave device (SAW-device). The SAW-device consists of an interdigital transducer (IDT) on a piezoelectric substrate, e.g. lithium niobate. Applying an AC voltage of appropriate frequency, the bidirectional IDT excites two counter-propagating surface acoustic waves on the substrate which are finally converted into bulk acoustic waves (BAW) within the fluid. The radiation direction of the BAW into the fluid is given by the Rayleigh angle $\vartheta_R = \sin^{-1}(c_{Fl}/c_{SAW})$; c_{Fl} speed of sound in the fluid and c_{SAW} SAW velocity of the piezoelectric substrate. Furthermore, the BAW in the fluid can be described by an acoustic beam which agitates a fluid stream due to the effect of acoustic streaming [1]. The shape of the acoustic beam and thus the fluid stream depends on the dimensions of the acoustic source of the acoustic beam. However, the acoustic streaming is still not completely understood. Particle Image Velocimetry (PIV) is a useful method to measure the agitated fluid stream and leads to an improvement of the understanding of the

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acoustic streaming. For fast fluid stream (mm/s and above) one obtains a so called jet in the fluid. First results of the frequency and power dependence of the excited jet in the range of 20- 1000 MHz have been reported by [2]. There, a 2D-PIV system was used to measure the jet agitated by a dry IDT (unloaded case). This means that solely one edge of the piezoelectric substrate and not the transducer itself was in contact to the fluid. The measurement results have been compared with simulation, assuming an acoustic source depending on the attenuation length of the SAW at the interface between fluid and substrate. However, the more practical usage of the SAW-device is to immerse it in the fluid, which means that the IDT is electrically and mechanically loaded by the fluid (loaded case). This leads to a greater variability in positioning the SAW-device and hereby the origin of the BAW related jets, which could be very useful, e.g. for mixing sediments or for flotation. In the loaded case the IDT is in contact to the fluid and the generation of the SAW is more complex. The dimension of the effective acoustic source of the BAW is given for the z-direction by the IDT aperture, since there is no SAW propagation in this direction. But for the y-direction the dimension of the effective acoustic source is not easy to determine, because this is the SAW propagation direction and the SAW generation is superimposed by reflection and damping effects. To our knowledge, thorough investigation on the actual SAW excitation for a fluid loaded device are still missing. In order to gain a first experimental insight into the loaded case we performed velocity measurements using the Defocus Digital Particle Image Velocimetry (DDPIV) [3]. This advanced PIV-technique allows volumetric measurements of the fluid motion induced by a SAW-device. Based on the measured velocity field we developed a procedure for the experimental determination of the acoustic source dimensions of the acoustic beam.

2. Experimental Setup

The experimental setup is shown in Fig. 1. It consists of a cuvette made of glass with optical quality and an inner size of (50 x 50 x 20) mm^3. The SAW-device was mounted on a holder that was fixed to the side wall of the glass cuvette and immersed in de-ionized water. Therefore the distance to the next wall is maximised and wall effects on the excited jet can be avoided. Furthermore the SAW-device was positioned in the middle of the cuvette. Hence an effect from the wall on either the upper or the lower jet is minimised. To guarantee a no-slip boundary at each wall, which means that the velocity of the fluid is zero, the cuvette opening was closed with a glass cover slip.

The DDPIV measurement technique used in this experiment was developed by TSI Inc. Its principle was first described in [4], where a single camera combined with a three-pinhole mask was used to obtain three-dimensional information about tracer particles seeded to the fluid. The advanced system used for the present measurement consists of three image sensors mounted into a triangular holder. The overlap between the fields of view of the three sensors determines the size of the measurement volume. Due to the different image sensor angles a triplet is formed in the image plane for each particle within the measurement volume, whereas the size of the triplet is proportional to the z-position of the particle. The closer the particle to the camera the larger the triplet, see Fig. 1. Furthermore the centre of the triplet determines the position in the x- and y-direction. The 3C-velocity (i.e. all three velocity components) of a particle in the measurement volume is characterised by the displacement of the particle identified in two subsequent images with well-known time interval in between. A more detailed description of the system can be found in [3].

In our measurements a dual cavity laser with a repetition rate of 15 Hz at a 532 nm wavelength was used to illuminate the whole cuvette from the front side towards the holder. The time between the double-pulses was adjusted for each electrical power level applied to the SAW-device during measurements to get a maximum particle displacement between two subsequent images which still allows reliable particle tracking. Furthermore the camera probe was orientated perpendicular to the side wall (see Fig. 1). In that way, the measurement volume of (50 x 50 x 20) mm^3 covered the entire volume of the glass cuvette. Within this volume, each individual particle was tracked with position uncertainty of about 20 μm in x- and y-direction and 40 μm in the z-direction. Hollow glass spheres with a mean diameter of 10 μm and a density of 1.1 g/cm^3 were used as tracer particles.

SAW-devices are characterized by several parameters, e.g. the size in terms of their IDT aperture b and length and the wavelength λ of the excited acoustic wave. Basically, the acoustic streaming effect neither depends on the size nor the wavelength. So these parameters can be chosen free of any restrictions, except experimental requirements, given by the limited spatial resolution and measurement volume of the flow measurement technique applied.

The dimension of the acoustic source for BAW generation depends in z-direction on the IDT aperture and in y-direction on the IDT length and the attenuation length of the SAW. The IDT length is 2.7 mm. Therefore we used an IDT aperture of b = 2 mm to keep the difference between z- and y-dimension small to ensure comparable data.

The choice of the wavelength of the SAW-device depends on the proportion between the attenuation length of the acoustic beam in the fluid and the measurement volume of the DDPIV. The measurement area in the plane of the agitated jet is (50 x 50) mm^2. Following [5], the equation for the attenuation length β^{-1} of a sound beam equals

$$\beta^{-1} = \frac{3}{16}\frac{c_{Fl}\rho\lambda^2}{\pi^2\mu} \tag{1}$$

with wavelength λ, viscosity μ, speed of sound c_{Fl} and density ρ. The jet length increases with increasing wavelength. For a SAW-device with a wavelength of 90 µm the attenuation length of the acoustic beam in water is in the order of 30 mm. By using such a device with a surface acoustic wave of 90 µm, the resulting acoustic beam dimension is maximised with respect to the limited spatial resolution of the measurement system and the size of the glass cuvette. Hence the jet length is maximised for the evaluation procedure and also wall effect can still be neglected.

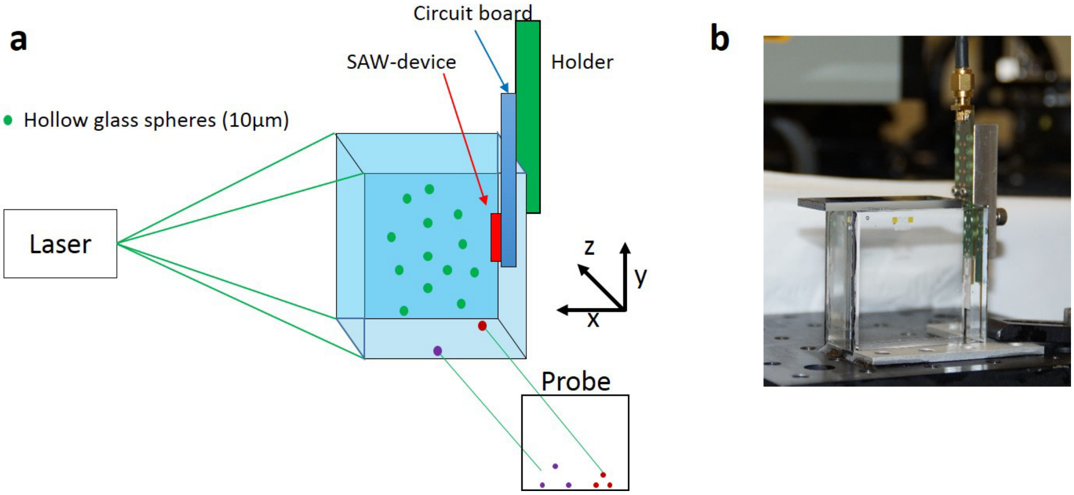

Fig. 1. (a) Sketch of the setup used in the experiment. The purple particle near to the camera probe leads to a larger triplet in the image plane as compared to the red particle which is in a greater z distance. (b) Image of the cuvette with IDT, circuit board, holder and glass cover slip.

3. Results

Fig. 2 illustrates the measurement result of the fluid motion induced by the SAW-device at an electrical power level of 250 mW. The bi-directional excitation of the SAW-device causes two narrow jets, which can be clearly identified. The semi-angle in between both jets amounts to $\approx 21^\circ$ and agrees very well with the Rayleigh-angle of approximated 22°, at a water temperature of 22 °C. Furthermore, both jets are very similar with respect to their width as well as their maximum velocity magnitude, see fig. 2b. Their lengths, however, slightly differ from each other. The reason for this non-symmetrical behaviour, which is independent of the electrical power level applied, has not yet been clarified and needs further investigation.

Measurements at six different power levels, ranging from 10 mW to 1 W, were conducted in total. For each measurement, the jet characteristics were analysed in detail, regarding the beam width in y- and z-direction. For this, a 2D-Gaussian beam model was fitted to the upper and the lower jet in the yz-plane along the x-direction at increments of 0.6 mm in length. Thereby, the resulting exp(−2)-widths of the 2D-Gaussian function determine the corresponding beam widths of the jets in y- and z-direction. For this, it is important to take the radiation angel of the acoustic beam into account, regarding actual beam width and position. Therefore further discussions of the beam width are done in reference to the position along the beam direction and all values are recalculated regarding the rayleigh angle.

As an example, fig. 3 illustrates the beam widths in z-direction for the lower jet at different power levels. In accordance with the diffraction on a small slit the beam width increases linearly with increasing distance to the SAW-device. However, the lower the electrical power applied the larger the beam width. This behaviour is somewhat

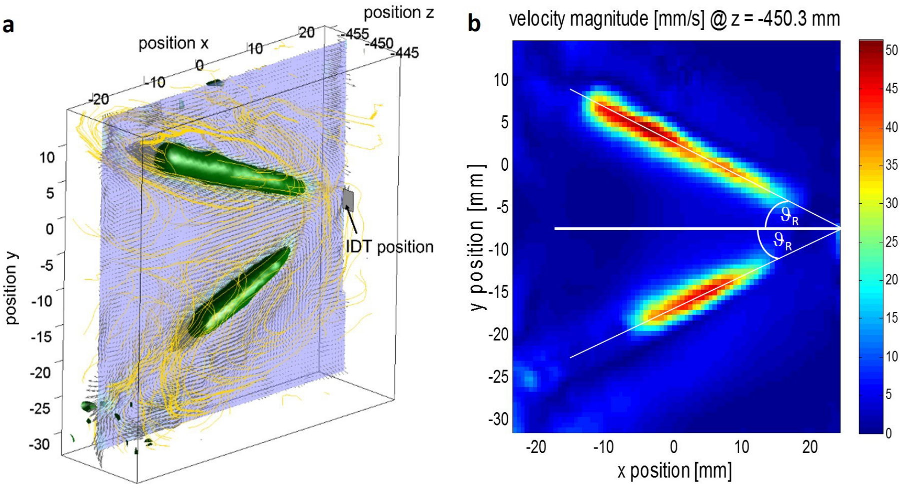

Fig. 2. (a) Shape of both agitated jets. The green isosurfaces represent areas with a velocity magnitude of 15 mm/s. (b) Velocity magnitude for both jets agitated under the Rayleigh angle ϑ_R for a plane in the middle of the IDT aperture.

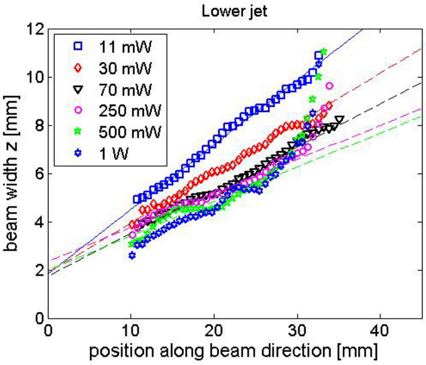

Fig. 3. Resulting beam width for the z-direction along the beam direction for different power levels for the lower jet

surprisingly, since the acoustic energy does not contribute to the theoretical description of the acoustic diffraction pattern. Therefore, we currently assume that the velocity uncertainty of the measurements, in conjunction with the evaluation procedure, causes an artificial widening of the jets at lower power levels. However, further measurements are necessary to investigate this counterintuitive phenomenon in more detail.

In order to estimate the size of the acoustic source of the SAW-device in y- and z-direction the measured beam widths were extrapolated by means of linear regression for each electrical power level, see fig. 3. In this way, the size of the acoustic source in one direction is given by the intersection between the linear regression and the ordinate. The estimated dimensions of the acoustic source, averaged over all measurements, are listed in table 1. The specified uncertainty corresponds thereby to the standard deviation ($\pm\sigma$).

The IDT aperture determines the size of the acoustic source in z-direction exactly. Hence, this well-known width can be used as reference to validate the estimation procedure as well. Within the uncertainty, a very good agreement between the aperture of the IDT ($b = 2$ mm) and the estimation (2.2 mm ± 0.4 mm) can be clearly identified. The size of the acoustic source in y-direction is not a-priori known, since not only the length of the IDT, but also the attenuation of the SAW determines the actual size of the acoustic source in y-direction. For the present setup, the total attenuation length of the SAW can be estimated after [6] to be 1.8 mm for our setup. In conjunction with the length of the IDT of 2.7 mm the actual size of the acoustic source in y-direction amounts to 4.5 mm, approximately. Again, a very good agreement between the experiment (4.4 mm±0.8 mm) and the theoretical estimation can be found, within the uncertainty of the measurements.

	Measured value [mm]	Expected value [mm]
y-direction	4.4 ± 0.8	4.5
z-direction	2.2 ± 0.4	2

Table 1. Acoustic source dimensions for the fluid loaded SAW-device.

Finally, with the knowledge about the size of the acoustic source the Fresnel number F can be calculated for both directions, depending on the distance to the acoustic source. For the present setup, the Fresnel number amounts to

$$F_y(\,\mathrm{mm}) = 1.3$$
$$F_z(\,\mathrm{mm}) = 0.3$$

at the largest distance to the SAW-device, meaning at the end of the measurement volume. With a Fresnel number of about 1, near-field diffraction has to be applied, when comparing the measurement results with simulations.

4. Conclusions

We have performed 3-dimension 3-component (3D3C)-flow measurements in a cuvette with a fluid loaded SAW-device using the V3V-System from TSI Inc.. The fluid motion induced by the SAW was successfully measured at six different electrical power levels. Based on this measurements a new evaluation process for the determination of the acoustic source dimensions was developed and has been proofed using the IDT-aperture as reference value. Also for the y-direction the process provides good accordance to the theoretical value. Based on the determination of the acoustic source dimension the calculation of the Fresnel number leads to a near-field problem. Therefore for further research, e.g. simulation of the fluid stream one hast to take into account the description of the acoustic beam by Fresnel diffraction.

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