Acoustic Streaming at Gigasonic Piston-Like Transducers

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Introduction

Acoustic streaming [1, 2] is a well known phenomenon. It plays an important role in various processes and surface preparation techniques. At ultrasonic frequencies it is extensively studied and mostly understood [3, 4]. To speed up the streaming one can increase the power or alternatively the frequency. Higher frequencies can also be an option to achieve better efficiency in small scale liquid processing such as mixing in micro-fluidics. Some works are known employing surface acoustic wave (SAW) transducers at several hundreds of MHz for this purpose [5]. Here, we investigate transducers developed to work as piston-like sources at about 2 GHz. The streaming originating from these transducers is analysed with Particle Shadow Velocimetry (PSV) techniques [6] and electrochemical measurements [7]. While large scale streaming has been observed to enter the whole cuvette as a jet flow, at the transducer surface also small scale streaming in form of vortices appears. Responsible for both effects is the high momentum transfer directly in front of the transducer, and possibly some heat convection, both due to the strong sound absorption at the gigasonic frequencies.

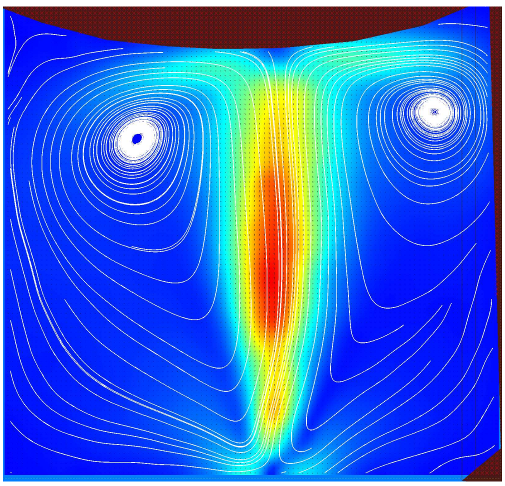

Figure 1: Streaming observed with PSV above the gigasonic transducer. View of the entire cuvette (ca. 1 cm in width). The maximum velocities resolved in this picture are about 5 cm/s. The red areas result from the water surface and field-of-view limitations due to the objective.

Experimental Setup

Two different setups are used for the measurements. For the PSV observations a Photron Fastcam SA5 camera with an Infinity K2 long distance microscope with different magnifications were used. For the backlight illumination we used a special LED flash [8] with adjustable pulse duration and power. All tests were done in DI-water with added melamin resin spheres (from one to ten micrometers in size). Electrochemical measurements were performed with a Gamry Instruments Reference 600 Potentiostat and a PI x-y-z-stage for an accurate positioning of the gold micro-electrode in an electrolyte solution, monitoring the reduction of Fe^{3+} to Fe^{2+} in the diffusion limiting regime (chronoamperometry). The high frequency transducer consists of an array of single emitting islands. The total area of this array is $3 \times 3\,\mathrm{mm}^2$. The transducer was driven at 10 watts of power with a backside cooling to avoid overheating of the chip. The cuvette on top of the transducer is made of PMMA and $1 \times 1 \times 1\,\mathrm{cm}^3$ in size. For the PSV-images a free MATLAB-script (PIVlab [9]) was used. A whole film of 200 subsequent pictures was analysed and the median was calculated to get a smoothed flow field.

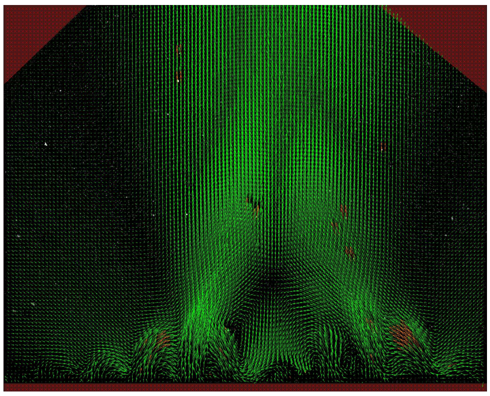

Figure 2: Streaming above the gigasonic transducer. The field of view is about 2 mm. The maximum velocities resolved in this picture are about 12 cm/s.

Results

Streaming observed with PSV

Directly above the transducer a vertical (rising) jet stream can be observed, even with the naked eye. Evaluations with PSV show a streaming away from the transducer in the middle of the cuvette and a flow downwards close to the walls. A PSV result with streamlines is shown in figure 1. The shape of this streaming resembles “Eckart” streaming [3], but at GHz-frequencies all sound should be attenuated within the first 100 µm of the adjacent liquid [10]. Thus, we encounter rather a case of "Lighthill" streaming [4] where the momentum is deposited in a small volume and a liquid jet is formed. Furthermore, at the transducer-liquid interface many small scale vortices can be observed, which rotate very fast. This can be seen in figures 2 and 3. These vortices at the bottom accompany the large scale streaming (which covers the entire cuvette). The small vortex flows might be caused by the inhomogeneous sound emission (i.e., the island structure of the transducer). A simulation of sound propagation and streaming with FEM (COMSOL [11]) indeed leads to eddies at the edges of a transducer island, see figure 4. Simulations and close-up PSV in figure 3 show similar spatial scales. The flow velocities, however, are much too high in the calculation, because the (unknown) effective displacement of the transducer front was set to 1 nm, which possibly is an overestimation.

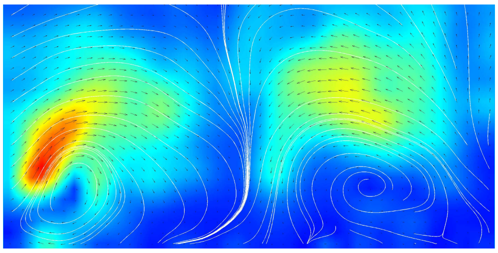

Figure 3: Streaming directly above the gigasonic transducer. The field of view is about 0.25 mm. The maximum velocities resolved at this distance are about 20 cm/s.

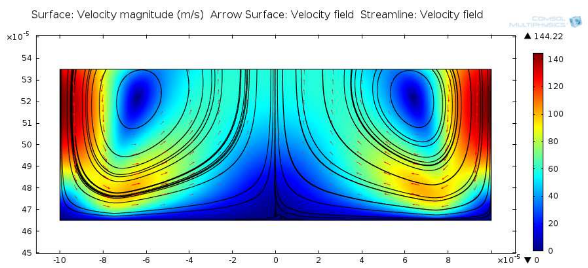

Figure 4: Simulated streaming above one single transducer island: direction of flow is upwards in the center, and downwards at the sides. Flow velocities are based on a surface (piston) displacement of 1 nm, and might be unrealistic high.

Streaming observed with electrochemistry

In close distance to the transducer, a horizontal scan was performed with the micro-electrode in electrolyte solution. The results shown in figure 5 reveal a high signal just in front of the emitter which indicates a very strong mass flow enhancement by the acoustic streaming. The flow is maximum in the center of the transducer, and a very repeatable fine structure probably reflects the small eddies due to the radiating islands.

Conclusions

Acoustic streaming at GHz frequencies has been observed. At this frequency the attenuation is very high, which means that the sound energy is completely attenuated within the first 100 µm. If one looks inside this layer it can be seen that small vortices are produced.

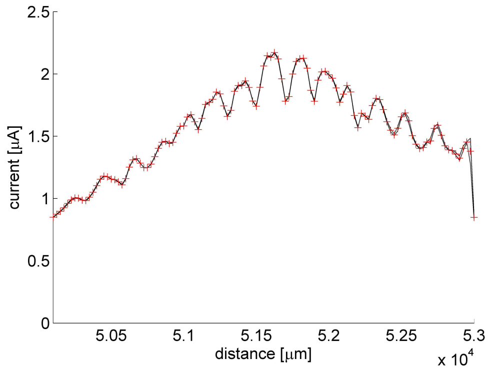

Figure 5: Electrochemical current at a gold micro-electrode near the transducer (horizontal scan at 130 µm distance). The small vortices next to the surface can clearly be seen as modulation of the curve.

This happens possibly at the edges of the single transducer islands. Due to momentum transfer of the emitted and absorbed sound, a jet-like large scale streaming of the liquid in the whole cuvette is started, which is an extreme realization of "Lighthill" streaming. An additional driving force for the large scale streaming consists in heat convection, as the absorbed sound energy is converted into kinetic energy and heat. Heating tests without sound, however, showed rather moderate convection in the cuvette, which leads to the conclusion that indeed gigasonic streaming is the main effect. Maximum velocities detected by PSV reach up to 20 cm/s close to the transducer interface, but might be higher due to finite resolution issues. With the strong liquid agitation observed, GHz piston-like transducers might serve as an alternative for SAW sound sources in microfluidics and for preparation techniques of small structured surfaces.

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