Modelling and Control of Acoustic Streaming in Standing Wave Fields

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Transducer-plane Streaming[3]

Experimental Investigation

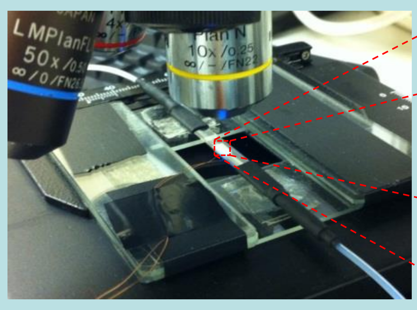

Fig. 1 Experimental setup

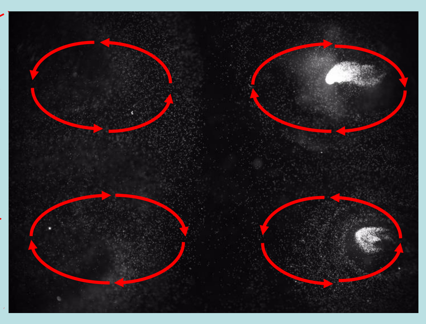

Fig. 2 Visualised streaming pattern

A four-quadrant acoustic streaming pattern, symmetric to the centre of the device and with the circulation plane parallel to the transducer face (Fig. 2), was experimentally visualised in our planar cell manipulation devices (Fig. 1). The mechanism behind this kind of streaming pattern has not previously been explained as it is different from the better-known Rayleigh and Eckart type streaming pattern, both in the shape of streaming flows it generates and in its genesis. In order to understand its origins, we present here a numerical method to simulate the streaming pattern in our capillary device and try to find its mechanism.

Model and Results

a. Model and numerical method

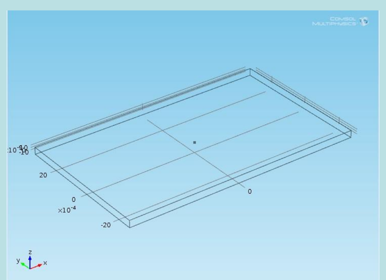

Fig. 3 Fluid-layer model

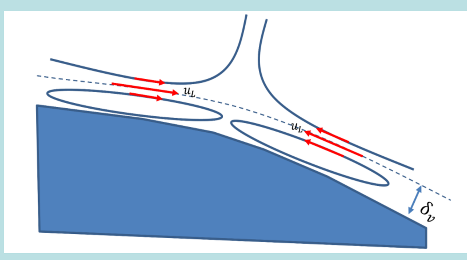

Fig. 4 Limiting velocity method

For numerical efficiency, only the fluid layer within the capillary is considered(Fig. 3). The streaming field is simulated from the limiting velocity method(Fig. 4), which was firstly introduced by Nyborg[4] and modified by Lee and Wang[5].

b. Numerical procedure

A linear acoustic model is firstly used to obtain the first-order acoustic pressure and velocity field, from which the limiting velocities can be derived. The limiting velocity method gives the localised limiting velocity at the edge of the inner streaming layer (Fig. 4) as a function of first-order field. These limiting velocities are applied as limiting velocity boundary conditions to a Stokes flow model to deduce the acoustic streaming field. Based on these two models, the particle trajectories are simulated by a combination of acoustic radiation forces and acoustic streaming induced drag forces.

c. Numerical results

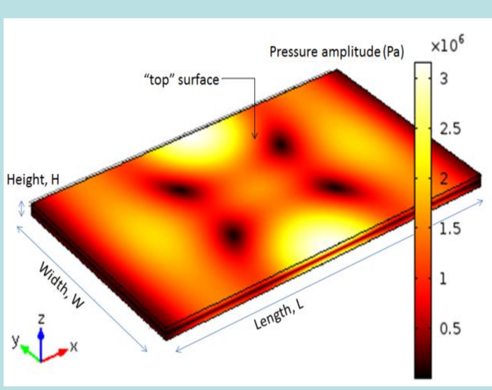

Fig. 5 Acoustic pressure field

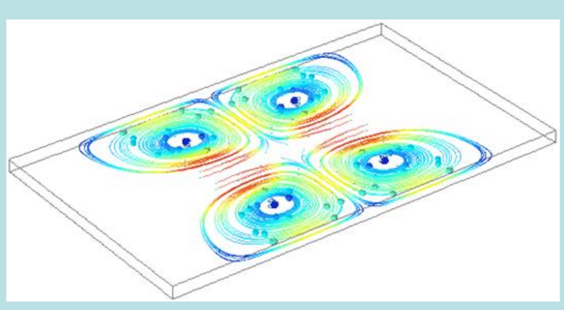

Fig. 6 Acoustic streaming dominated particle trajectories

As only the fluid layer within the capillary is considered, the transducer excitation is replaced by a sinusoidal vibration of its bottom surface. The vibration is driven at the half wavelength resonance(Fig. 5). From the simulated trajectories of 1μm particles(Fig. 6), we can see that a four-quadrant vortex pattern symmetric to the centre of the device is obtained, which is the same with the experimental visualisation.

Discussion

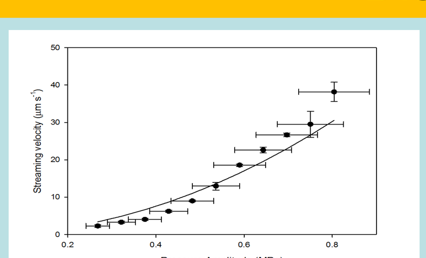

Fig. 7 Comparison of magnitude of streaming velocity between experiments and simulations

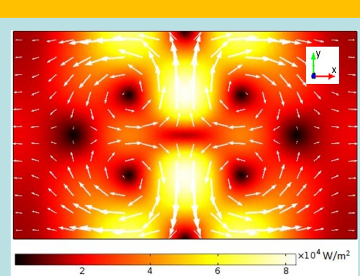

Fig. 8 Active acoustic intensity field on limiting velocity boundaries

We find good agreement is obtained between numerical and experimental methods. Examining the limiting velocities on limiting velocity boundaries, we found that they are approximately proportional to the active sound intensity field. Plotting the active acoustic intensity on the limiting velocity boundaries in the model, a four-quadrant vortex pattern is also obtained(Fig. 8), which is closely related to the streaming pattern experimentally visualised and numerically simulated.

Abstract

In acoustofluidic particle manipulation and sorting devices streaming flows are typically found in addition to the acoustic radiation forces. Understanding their origins is essential for creating designs to limit or control this phenomenon.

In addition to the classical Rayleigh streaming, experimental work from various groups has described 'unusual' acoustic streaming, transducer-plane streaming, typically a four-quadrant streaming pattern with the circulation parallel to the transducer face. The cause of this kind of streaming pattern has not been previously explained as it is different from the well-known classical streaming patterns such as Rayleigh streaming[1] and Eckart streaming[2].

In this work, both 3D Rayleigh streaming and transducer-plane streaming are investigated using both experimental and numerical methods. Furthermore, acoustic streaming field due to two orthogonal standing wave fields in a microfluidic device is simulated and analysed.

Acoustic Streaming in Standing Wave Fields:

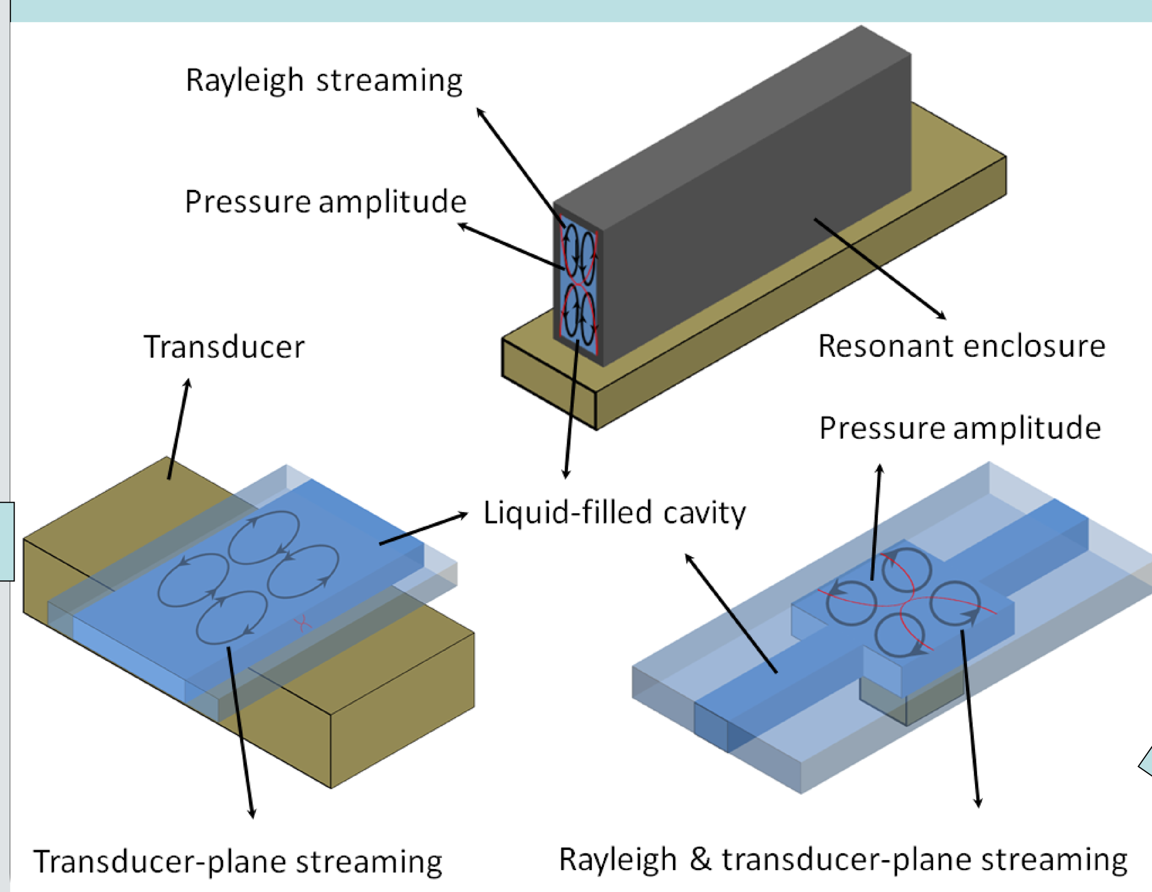

Fig. 9 Acoustic streaming patterns in resonant enclosures

Conclusion & Outlook

- The transducer-plane streaming has been simulated and the mechanism behind this pattern has been found. Simulations show good agreement with experiments.
- 3D Rayleigh streaming in a cuboid and acoustic streaming due to 2 orthogonal standing waves in a microfluidic device are modelled and successfully compared with the experimental investigations.
- In order to fully control the streaming field, the effects of controllable outer conditions (e.g. surface profile) on the acoustic streaming field will be investigated from both numerical and experimental methods.
- New designs to efficiently concentrate submicron/Nano particles using controlled acoustic streaming patterns will be introduced.

References

[1] L. Rayleigh, *On the circulation of air observed in Kundt's tube, and on some allied acoustical problems.* Phil. Trans., 1883. **175**: p. 1-21.

[2] C. Eckart, *Vortices and streams caused by sound waves.* Phys. Rev., 1947. **73**(1): p. 68-76.

[3] J. Lei, P. Glynne-Jones, and M. Hill, *Acoustic streaming in the transducer plane in ultrasonic particle manipulation devices*. Lab on a Chip, 2013, **13**, 2133-2143

[4] W.L. Nyborg, *Acoustic streaming due to attenuated plane waves.* J. Acoust. Soc. Am., 1953. **25**(1): p. 68-75

[5] C.P. Lee and T.G. Wang, *Near-boundary streaming around a small sphere due to 2 orthogonal standing waves.* Journal of the Acoustical Society of America, 1989. **85**(3): p. 1081-1088

[6] J. Lei, M. Hill, and P. Glynne-Jones, *Numerical simulation of 3D boundary-driven acoustic streaming in microfluidic devices*. Lab on a Chip, 2014, 14, 532-41

[7] P. B. Muller, M. Rossi, Á. G. Marín, R. Barnkob, P. Augustsson, T. Laurell, C. J. Kähler and H. Bruus, *Ultrasound-induced acoustophoretic motion of microparticles in three dimensions.* Phys. Rev. E, 2013, **88**, 023006

Rayleigh Streaming[6]

Rayleigh streaming has been visualised and analysed for more than a century. However, most investigations are based on two dimensional models. The 3D Rayleigh streaming pattern in a cuboid is simulated and the effects of Rayleigh streaming on the movement of particles at different sizes are presented. Simulations show good agreement with experimental measurements.

Model and Results

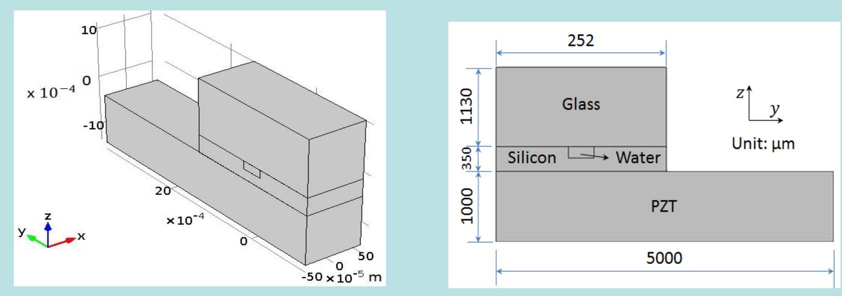

Fig. 10 Full model and yz cross-section

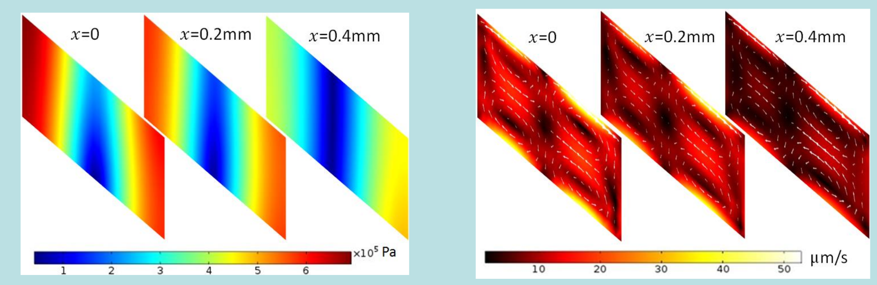

Fig. 11 Simulated acoustic pressure field (left) and acoustic streaming field (right)

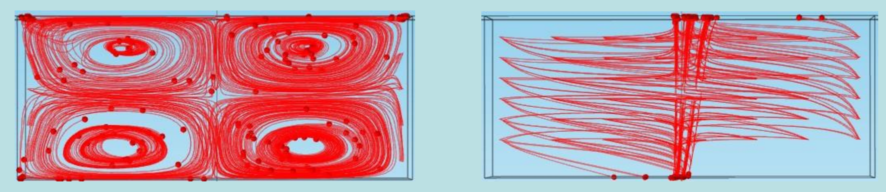

Fig. 12 Simulated trajectories of 0.5μm particles (left) and 5μm particles (right)

The figures above show respectively the model and simulated results. The whole numerical procedure is the same with the one used to simulate the transducer-plane streaming.

Discussion

The modelled results were compared to experimental investigations by Muller et al.[7]. It is found that both the magnitude of streaming velocities and streaming pattern are in good agreements. Due to the variation of acoustic field in x direction, numerical results in 2D models cannot completely represent the streaming field in real devices.

Acoustic streaming due to two orthogonal standing waves[6]

This work investigates an unusual in-plane streaming pattern in a microfluidic device where a two orthogonal standing wave is established. The origin of this streaming has not been previously fully described and its characteristics cannot be explained from the classical theory of Rayleigh streaming.

Model and Results

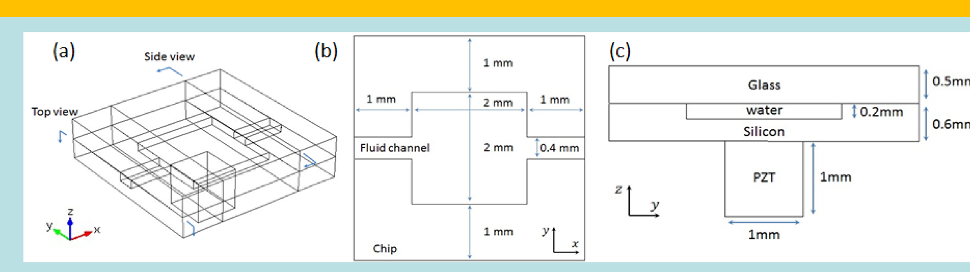

Fig. 13 Illustration of the design

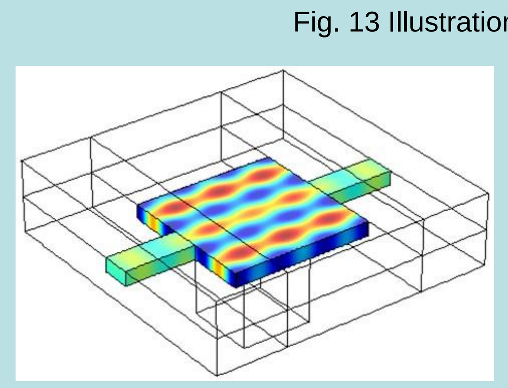

Fig. 14 Acoustic pressure field

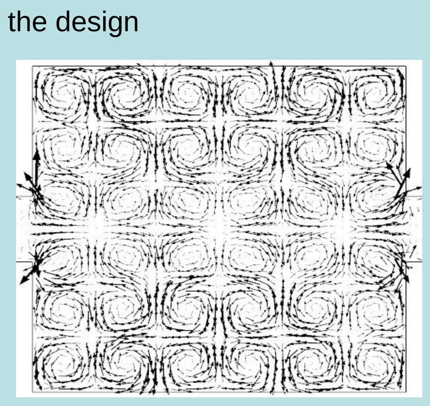

Fig. 15 Acoustic streaming field

The figures above show respectively the design (Fig. 13), acoustic pressure field (Fig. 14), and the acoustic streaming field (Fig. 15). It can be seen from the simulated results that a two orthogonal standing wave field in the central square area of the fluid channel is established and, in certain planes parallel to the transducer face, 6x6 vortex pattern is obtained, which is the same with experimental visualisation (not shown).

Discussion

The simulated in-plane streaming pattern was in good agreement with the experimental visualisation. The mechanism behind it is shown to be related to the active sound intensity field (not shown), which supports our previous findings on the mechanism of the in-plane acoustic streaming pattern visualised and modelled in a thin-layered capillary device.

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