OBSERVATION OF INVERSE TRANSDUCER-PLANE STREAMING PATTERNS

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Transducer-plane streaming are acoustic streaming patterns whose orientations are parallel to the driving boundaries. In this paper, by reporting a new transducer-plane streaming pattern, which we call here inverse four-quadrant transducer-plane streaming, in an ultrasound-excited thin-layer device, we illustrate the importance of the travelling wave component and emphasize its phase difference with the standing wave component in thin-layer standing acoustofluidic manipulation devices on the formation of transducer-plane streaming patterns. A model was created for solving the three-dimensional acoustic streaming fields from limiting velocities derived from predefined acoustic fields, capturing both the standing wave and travelling wave components and their phase relations. It was found that, by tuning the phase difference, φ, reversed streaming patterns can be excited and could be shifted along the fluid channel, which could provide insights for the control of transducer-plane streaming in thin-layer acoustofluidic devices for a wide range of applications, such as nanoscale particle manipulation and particle transport/propulsion.

Keywords: acoustic streaming, transducer-plane streaming, acoustofluidics

1. Introduction

Acoustic streaming is steady fluid motion driven by the absorption of acoustic energy in a fluid. A premise behind the control of acoustic streaming for enhancing or suppressing acoustic streaming for many acoustofluidic applications is to understand the driving mechanisms of acoustic streaming patterns within acoustofluidic devices. In most bulk acoustofluidic particle and cell manipulation systems of interest, the acoustic streaming fields are generally dominated by boundary-driven streaming[1], which arises from the acoustic attenuation within the acoustic boundary layer due to the non-slip condition on the walls of the fluid channel[2].

Classical boundary-driven streaming includes streaming vortices both inside and outside of the acoustic boundary layer. While Rayleigh streaming patterns, which have streaming vortices with components perpendicular to the driving boundaries, have been extensively studied within the field of acoustic particle trapping and manipulation in last decades[3-7], there are acoustic streaming patterns observed experimentally in acoustofluidic particle manipulation devices that cannot be explained by Rayleigh’s classical theory[8-13]. Particularly, acoustic streaming patterns whose orientations are parallel to the driving boundaries and the transducer radiating surface have been observed in thin-layer standing acoustofluidic manipulation devices, which are adverse to the conditions found in Rayleigh streaming and thus are referred to as transducer-plane streaming[10]. Recently, we have explored the mechanisms behind a four-quadrant transducer-plane streaming pattern[10] and an eight-octant transducer-plane streaming pattern[11], of which each streaming vortex respectively occupies approximately a quadrant and an octant of the visualisation plane parallel to
the driving boundaries (and the transducer face). It was found that the limiting velocity fields, which drive the transducer-plane streaming patterns, are closely related to the active sound intensity field on the driving boundaries (which tends to circulate about pressure nodal points[14]).

In this work, we present a new transducer-plane streaming pattern, which is typically an inverse pattern to that we have observed before[10], from both experimental measurements and numerical modelling. We first introduce the new transducer-plane streaming pattern observed in a thin-layer glass capillary device, which has not been discussed or shown experimentally before, and then investigate the underlying physics of four-quadrant transducer-plane streaming patterns with a numerical model.

2. Experiments

The experiments were conducted in a simple transducer-capillary device, shown in Fig. 1(a), which is a widely used acoustofluidic system for many microfluidic applications. The cross-section of the experimental device is depicted in Fig. 1(b), in which properties and dimensions of device layers are presented. The measurements were performed within xy horizontal planes and the investigation areas were above the transducer radiating surface. More detailed PIV setup and measuring procedures are similar to those shown in refs.[9, 10] The streaming pattern observed (at the half wavelength resonant frequency within the fluid layer of the capillary in the z direction) is shown in Fig. 1(d), where PIV results of the streaming field, calculated from 1 µm polystyrene particles (Fluoresbrite microspheres, Polysciences Inc.), is presented. It can be seen that a four-quadrant acoustic streaming pattern, in which each vortex occupies approximately one quadrant of the viewed xy horizontal plane, is formed. The plane of these vortices is parallel to the transducer radiating surface (i.e., perpendicular to the axis of the main standing wave in the z direction), as is the case for the four-quadrant transducer-plane streaming we have demonstrated previously in another standing acoustofluidic manipulation device[10], but in a different direction on each streaming vortex. We thus call it here inverse four-quadrant transducer-plane streaming.

![Fig. 1. Observation of a new transducer-plane streaming pattern in a thin-layer acoustofluidic manipulation device: (a) the experimental device; (b) yz cross-section, materials and dimensions of the device; and (c) PIV results of the acoustic streaming velocity field measured at plane z = 0, where the reference arrow at the right-bottom corner shows a velocity of 30 µm/s.](image-url)
3. Numerical method

To understand the genesis of this new transducer-plane streaming pattern and what makes it different to the four-quadrant pattern observed previously[10], a numerical model was created to simulate the acoustic and streaming fields in the experimental device using the finite element package COMSOL 5.2. The 3D model is shown in Fig. 2(a), where only the third-quadrant of the fluid channel was considered as the fluid channel and the acoustic streaming pattern are symmetric to planes $x = 0$ and $y = 0$. The whole numerical procedure was split into two steps:

**Firstly, definition of acoustic fields.** In this work, we defined the acoustic pressure field from combinations of cavity modes and TW modes. By doing so, compared to the linear acoustic model we made in previous work, where a normal distribution of boundary vibration was applied to approximate the 3D first-order acoustic fields in fluid channels[9, 10], we are able to obtain more insights into the relative significance of the travelling wave (TW) and standing wave (SW) components[11] on the resulting transducer-plane streaming patterns. The 3D first-order acoustic pressure field, $p_1$, established in the fluid channel is decomposed into two components, a SW component, $p_{1s}$, and a TW component propagating along the fluid channel, $p_{1t}$,

$$p_1 = p_{1s} + p_{1t},$$

$$p_{1s} = p_{0s} \cos(k_{xs}x) \cos(k_{ys}y) \sin(k_{zs}z)e^{i\omega t},$$

$$p_{1t} = p_{0t}e^{ik_{xt}x} \cos(k_{yt}y) \sin(k_{zt}z)e^{i(\omega t+\phi)},$$

where the second subscripts $s$ and $t$ indicate the SW and TW components respectively, $p_0$ is the acoustic pressure amplitude, $\omega$ is the angular frequency, $k_x, k_y$, and $k_z$ are the wave numbers in the $x$, $y$ and $z$ directions and $\phi$ indicates the phase difference between the SW and TW components.

**Then, modelling of acoustic streaming fields.** In this work, we have applied the limiting velocity method[15] based on the perturbation method[16] to model the 3D outer streaming fields in the capillary device. This method is more computationally efficient than the conventional numerical method by considering Reynolds stresses[3, 6], the volume forces representing the time-averaged acoustic momentum flux due to the acoustic dissipation near the no-slip walls[17]. More detailed description of the limiting velocity method can be found from Ref.[18].

In this step, the limiting velocity field solved above was applied as a limiting velocity boundary condition. Outside of the acoustic boundary layer, the governing equations for the second-order streaming velocities, $u_2$, and the associated pressure fields, $p_2$, are

$$\nabla p_2 = \mu \nabla^2 u_2,$$

$$\nabla \cdot u_2 = 0,$$

where $\mu$ is the dynamic viscosity of the fluid. Here, the bottom and top surfaces ($z = \pm h/2$) were considered as limiting velocity boundary conditions, surfaces $x = 0$ and $y = 0$ were symmetric conditions and the remaining were no-slip boundary conditions.

4. Results

It should be noted that, prior to defining the acoustic field using Eqs. (1), the linear acoustic model applied in previous work[9, 10] was used to predict the total 3D acoustic field, which can narrow the searching list of SW and TW combinations for the formation of this inverse four-quadrant transducer-plane streaming pattern.

It was found that the total acoustic field shown in Fig. 2(b), which is close to the (1, 2, 1) cavity mode but includes both SW and TW components, gives rise to the inverse four-quadrant active intensity pattern, which is similar to that driving the four-quadrant transducer-plane streaming pattern in another device[10]. To distinguish the contributions of respectively the SW and TW components in this device, we thus define here a (1, 2, 1) SW mode (shown in Fig. 2(c)) according to the resulted total acoustic pressure field and examine the active intensity patterns under different traveling wave modes. Through parametric studies, we found that, for pressure expressions presented in Eqs. (1), a combination of (1, 2, 1) SW mode and (t, 0, 1) traveling wave mode (see Fig. 2(d)) and a
phase difference \( \varphi = \pi/2 \) between them are required to produce the inverse four-quadrant active intensity pattern. The modelled acoustic streaming fields driven by pressure fields illustrated above are presented in Fig. 2(e)-(f), where a well-formed transducer-plane streaming vortex can be seen in the quadrant model, which is the same with that of four-quadrant transducer-plane streaming pattern[10] but rotates in an opposite direction.

Until now, in two glass capillaries at different fluid channel sizes, we have shown the full set of well-formed four-quadrant transducer-plane streaming patterns, in which the streaming vortex in each quadrant of the vertical (z-direction) pressure nodal plane rotates in opposite directions. Although the first order acoustic fields established in these two devices are the same combination of SW and TW components, the phase differences between the SW and TW components in these two devices differ by \( \pi \).

Fig. 2: Modelling of acoustic and streaming fields in the experimental device: (a) the 3D model (10 × 7.5 × 1 mm\(^3\)) considered, where the dash-dot lines show the symmetry planes; magnitudes of (b) the total first-order acoustic pressure (Pa); (c) the standing wave pressure component (Pa); (d) the travelling wave pressure component (Pa); (e) the 3D acoustic streaming velocity field (m/s), where velocity vectors are shown at two heights within the chamber (z positions of one third and two thirds of the chamber height); and (f) \( xy \) view of the streaming field shown in (e), where the five-pointed star represents the vortex centre.

5. Conclusions

In this paper, by showing an inverse four-quadrant transducer-plane streaming pattern from numerical modelling and experimental measurements, we have presented the full set of four-quadrant transducer-plane streaming patterns in thin-layer acoustofluidic manipulation devices and demonstrated their driving mechanisms.

An important next step is to understand how device structures, ultrasonic excitations and fluid channel dimensions affect the phase difference between the SW and TW components \( \varphi \) in a 3D acoustic field established in the fluid channel of an acoustofluidic device, which could provide means for the control of \( \varphi \) in a single thin-layer acoustofluidic manipulation device. By establishing this, a wide range of applications could be realised.

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