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Acoustic streaming induced by two orthogonal ultrasound standing waves in a microfluidic channel

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ABSTRACT

A mathematical model is derived for acoustic streaming in a microfluidic channel confined between a solid wall and a rigid reflector. Acoustic streaming is produced by two orthogonal ultrasound standing waves of the same frequency that are created by two pairs of counter-propagating leaky surface waves induced in the solid wall. The magnitudes and phases of the standing waves are assumed to be different. Full analytical solutions are found for the equations of acoustic streaming. The obtained solutions are used in numerical simulations to reveal the structure of the acoustic streaming. It is shown that the interaction of two standing waves leads to the appearance of a cross term in the equations of acoustic streaming. If the phase lag between the standing waves is nonzero, the cross term brings about circular vortices with rotation axes perpendicular to the solid wall of the channel. The vortices make fluid particles rotate and move alternately up and down between the solid wall and the reflector. The obtained results are of immediate interest for acoustomicrofluidic applications such as the ultrasonic micromixing of fluids and the manipulation of microparticles.

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1. Introduction

The operation of microfluidic systems is based on the use of physical effects produced by ultrasound waves in a microscale environment. Characteristic dimensions of microfluidic devices lie in the range of several micrometers to several hundred micrometers. The sizes of objects whose behavior and properties are investigated in microfluidics are from several nanometers to several micrometers. These conditions require the application of acoustic wave fields with frequencies from the upper kHz range up to several tens of MHz, so processes that occur in microfluidic devices are of ultrasonic nature.

The present work studies theoretically acoustic streaming in an ultrasonically actuated microfluidic channel. Acoustic streaming, along with acoustic radiation forces [1], is one of the main tools that are used in microscale acoustofluidics for contactless manipulation of various objects, such as functionalized microparticles and biological cells [2–4]. Another challenging problem of microfluidics, where acoustic streaming plays a key role, is ultrasonic micromixing of liquid solutions in microfluidic devices. The use of acoustic streaming allows one to enhance this process [5–7]. A detailed special-purpose review on applications of acoustic streaming in microfluidic systems has been provided by Wiklund et al. [8].

In acoustofluidic devices, acoustic streaming is generally boundary layer driven streaming, which is caused by boundary layer effects between an acoustically excited fluid and solid boundaries [8]. A first mathematical description of boundary layer driven streaming was given by Rayleigh [9]. Based on a number of assumptions, he derived a solution for the case of a plane standing wave propagating between two planar rigid walls. His solution predicts acoustic streaming outside the viscous boundary layer and is commonly referred to as "Rayleigh streaming" or "outer streaming". Further development of Rayleigh's theory has been performed by Schlichting [10], Westervelt [11], and Nyborg [12–14]. These studies are reviewed by Boluriaan and Morris [15] and Wiklund et al. [8]. Hamilton et al. [16] have obtained an analytical solution for acoustic streaming generated by a standing wave between two planar rigid walls that allows one to calculate the streaming field both outside and inside the boundary viscous layer. Recently, Doinikov et al. [17] have generalized the solution of Hamilton et al. [16] to the case of two orthogonal standing waves of the same frequency and shown that the interaction between the waves generates acoustic streaming that makes the fluid rotate in planes parallel to the walls. There are also a number of numerical simulations of boundary layer driven streaming, which are reviewed by Boluriaan and Morris [15], see also [18,19].

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The theoretical studies described above assume that the boundaries, in which an ultrasonically activated fluid is confined, are fixed. In other words, they assume that it is not the vibrational motion of the boundaries that drives the fluid. However, in acoustofluidic devices, the fluid is commonly excited through the vibration of microchannel walls. Muller et al. [18] and Lei et al. [19,20] performed numerical simulations of boundary layer driven acoustic streaming in bulk acoustic wave (BAW) based systems; see also [21] for additional theoretical and experimental data. BAW-based systems are actuated by a piezo transducer attached to the wall of a liquid-filled microchannel. As a result, an acoustic wave is generated in the fluid, which propagates perpendicularly to the vibrating wall. Lei et al. [19,20] showed that, in addition to the classical boundary-driven acoustic streaming, such as Rayleigh streaming whose vortex plane is perpendicular to the transducer face, streaming flows can arise in a plane parallel to the transducer face. Such streaming patterns, named transducer-plane streaming, are typically generated in planar microfluidic resonators, where the acoustic energy gradients in the lateral directions parallel to the transducer face are significant in addition to the gradients perpendicular to the transducer face. The existence of this kind of acoustic streaming is confirmed experimentally [8,19,22].

In recent years, surface acoustic wave (SAW) based systems have gained wide application in microfluidics [23–26]. SAW-based systems are actuated by leaky surface waves that are excited in a solid substrate. These waves propagate along the solid-fluid interface of a microfluidic channel and emit acoustic energy into the fluid layer. As a result, acoustic waves, and hence acoustic streaming, are generated in the fluid. In the context of our theoretical study, relevant works to be mentioned are as follows. Vanneste and Bühler [27] have calculated acoustic streaming produced by a leaky surface wave in a fluid layer with a free boundary. Based on a number of assumptions, they derived linear analytical solutions and then solved numerically the equations of acoustic streaming. Nama et al. [28] applied a finite element scheme to model numerically the acoustophoretic motion of particles inside a liquid-filled PDMS microchannel due to acoustic radiation forces and acoustic streaming. They used impedance boundary conditions to model the channel walls and assumed that the system was actuated by two counter-propagating surface acoustic waves that formed a standing wave in a piezoelectric material interfacing the liquid channel. Their results showed that excited acoustic fields were significantly different from those observed in BAW-based systems. Recently, Doinikov et al. [29] have derived analytical solutions for acoustic streaming in a microfluidic channel confined between an elastic solid wall and a rigid reflector, assuming that the acoustic streaming is generated by a standing wave that is created by two counter-propagating leaky surface waves induced in the solid wall. A discussion of rotational motion that can be induced by acoustic streaming in SAW-driven systems is provided by Bernard et al. [30].

The aim of our study is to develop a theory that describes acoustic streaming in a microfluidic channel confined between an elastic solid wall and a rigid reflector. We assume that the ultrasonic actuation of the above system is produced by two orthogonal ultrasound standing waves of the same frequency that are created by two pairs of counter-propagating leaky surface waves induced in the solid wall. It should be emphasized that the standing waves are assumed to have, in general, different magnitudes and phases. In Section 2, analytical solutions to the equations of acoustic streaming are derived. In Section 3, numerical examples are provided that demonstrate the structure of the acoustic streaming under study. To anticipate, we show that, if the phase lag between the driving standing waves is nonzero, the acoustic streaming produces circular vortices in which fluid particles rotate about axes perpendicular to the solid wall of the channel and move alternately up and down between the solid wall and the reflector.

2. Theoretical model

2.1. Problem formulation

Let us consider a fluid layer that is confined between an elastic solid wall and a rigid reflector, as shown in Fig. 1. The solid wall occupies the half-space with $z > 0$, the fluid is within the spatial layer with $-h < z < 0$, and the reflector is located at $z = -h$. We assume that two pairs of counter-propagating leaky surface waves are excited in the solid wall. The waves are emitted in the fluid, reflected at the channel top and produce two orthogonal ultrasound standing waves in the channel, which propagate along the x and y axes. The standing waves are assumed to have the same frequency but, in general, different magnitudes and phases.

2.2. Linear solutions

The linear fluid velocity can be represented as

$$\boldsymbol{v} = \boldsymbol{v}_x(x,z,t) + \boldsymbol{v}_y(y,z,t), \tag{1}$$

where

$$\boldsymbol{v}_x = [v_{xx}(x,z)\boldsymbol{e}_x + v_{xz}(x,z)\boldsymbol{e}_z]e^{-i\omega t}, \tag{2}$$

is the velocity produced by the standing wave propagating along the x axis and

$$\boldsymbol{v}_y = [v_{yy}(y,z)\boldsymbol{e}_y + v_{yz}(y,z)\boldsymbol{e}_z]e^{-i\omega t}, \tag{3}$$

is the velocity produced by the standing wave propagating along the y axis. The expression for $\boldsymbol{v}_x$ was derived in our previous paper [29]. An expression for $\boldsymbol{v}_y$ can be written by analogy, just replacing x with y. As a result, expressions for the velocity components can be represented as

$$v_{\tau\tau}(\tau,z) = 2i[iks_{1\tau}(z) - q_v s_{2\tau}(z)]\sin(k\tau), \tag{4}$$

$$v_{\tau z}(\tau,z) = 2[q_f s_{3\tau}(z) + iks_{4\tau}(z)]\cos(k\tau). \tag{5}$$

Here, τ denotes x or y and the following definitions are used:

$$s_{1\tau}(z) = A_{1\tau}e^{q_f z} + A_{2\tau}e^{-q_f z}, \tag{6}$$

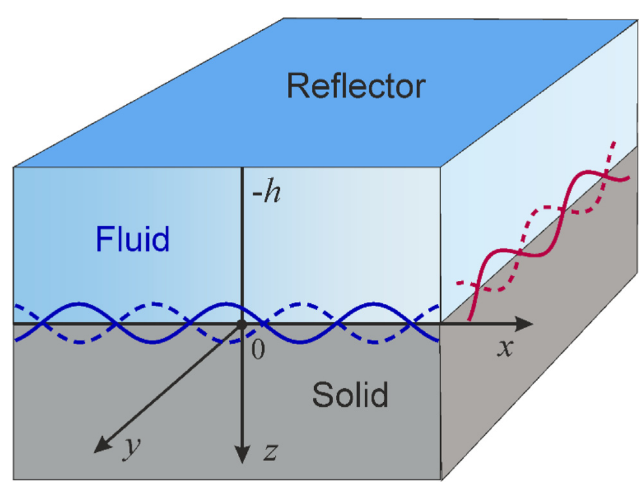

Fig. 1. A fluid layer of height h is located between an elastic solid wall and a rigid reflector. Two orthogonal surface acoustic waves are excited in the solid wall. The waves are emitted in the fluid, reflected at the channel top and produce two orthogonal ultrasound standing waves in the channel, which propagate along the x and y axes.

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