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Study of the onset of the acoustic streaming in parallel plate resonators with pulse ultrasound

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ABSTRACT

In a previous study, we introduced pulse mode ultrasound as a new method for reducing and controlling the acoustic streaming in parallel plate resonators (Hoyos and Castro, 2013). Here, by modifying other parameters such as the resonator geometry and the particle size, we have found a threshold for particle manipulation with ultrasonic standing waves in confined resonators without the influence of the acoustic streaming. We demonstrate that pulse mode ultrasound open the possibility of manipulating particles smaller than 1 μm size.

1. Introduction

Acoustic streaming (AS), is a steady fluid flow generated by the viscous attenuation of high amplitude acoustic waves. Part of the energy lost through acoustic dissipation is imparted to the fluid as steady momentum.

An acoustic resonator, is a cavity where a piezoelectric transducer is placed behind one of the walls. The other wall serve as passive reflector. The superposition of the emitted and reflected waves is known as an ultrasonic standing wave (USW). It was demonstrated that USW can be used to trap, to concentrate, to move and to spatially localize micron-sized objects in suspension in the pressure nodal or antinodal planes [2]. When USW are generated by the action of the primary radiation force **PRF** (or acoustic force *Fac*), the attenuation occurs in the boundary layer close to the walls of the cavity. The streaming generated is called Rayleigh streaming [3,4].

Our devices are parallel plate resonators where we use the **PRF** to levitate objects towards the node or the antinode, as depicted in Fig. 1. Particles are going to be focused at an equilibrium position which correspond to the balance between the gravitational and the acoustic forces. That equilibrium position we call the levitation plane. There, the transverse component of the **PRF** moves particles towards the regions of maximum acoustic energy. The transverse force is at least one order of magnitude smaller than the **PRF** [5].

Generally veiled by main flows or neglected when micron-sized species are manipulated the AS becomes visible when the suspension is composed of sub-micron-sized particles; species are focused close to the levitation plane generating a diffuse layer [1]. The forces implied in the AS are very small compared to the **PRF** but high enough for dragging the particles. The flow velocities generated by the streaming span from tenths to hundreds of μm/s [4,6]. Particles take some time to be focused close to the levitation plane. This time is the relaxation time that could be less than one second for micron-sized particles and is inversely proportional to the particle volume [7].

The AS is also established after a dissipation time that is longer than the relaxation time and independent of the particle volume [4]. Particles smaller than 1 or 2 μm are dragged out by the AS before being focused at the nodal plane [8]. The study of the competition between **PRF** and AS forces is the main goal of this paper in order to manipulating them independently.

1.1. Pulse mode ultrasound

In [1], we introduced pulse mode ultrasound for controlling/reducing the AS for 883 nm latex particles. We found that in continuous mode sub-micron-sized particles are drafted by the AS. Nevertheless the **PRF** produces an average relaxation time

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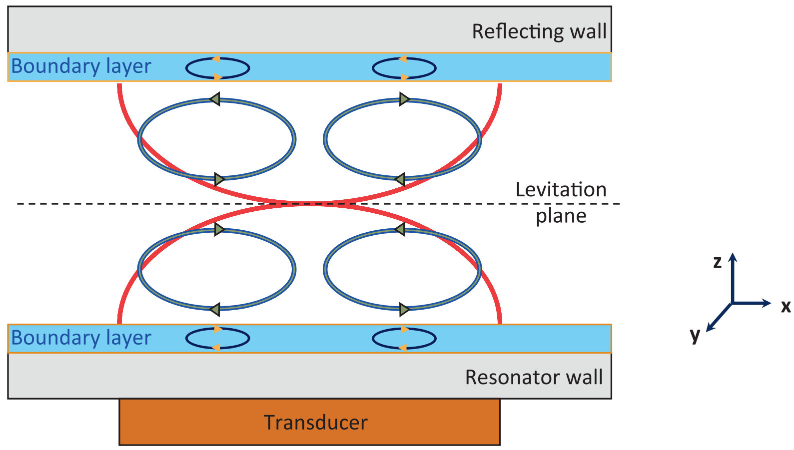

Fig. 1. Schematic view of the acoustic streaming observed in parallel plate resonators. Particles are spread at the resonator thickness and concentrated at the node or the antinode. Once the USW are applied, **PRF** pulls them to the levitation plane.

toward the node of 35 s. A preliminary study on the relaxation of sub-micron sized particles will be presented in the last part of this paper. A layer of sub-micron sized particles has some μm of thickness due to diffusion. Nevertheless, it is difficult to determine when the concentration profile is reached. The AS visualized as the transverse motion of particles destroy the equilibrium visible after 20 s, time in which the first clumps appear (at the nodal plane, 3a). Clumps are formed at the node with sizes of roughly 1–30 μm of diameter. In Video 1 (ESI) we show the particles vortex created by the AS at the levitation plane.

We use pulse mode acoustics to explore particle manipulation. At the established resonance frequency in the resonator, we generate a number of bursts *n* as schematized in Fig. 2 during a time *Tp*. The bursts are generated after a repetition time, *Tt*. Here we use the concept of Duty cycle that we call Pulse mode factor. Pulse mode factor is the ratio between the time of "acoustic on" divided by the total time (acoustic on + acoustic off).

We can maintain particle levitation and aggregation by reducing at the same time the AS. For **PRF** and AS, the characteristic times are different being the onset of the AS bigger than **PRF** focusing time. A typical pattern of particles under AS formed in continuous mode is shown in Fig. 3a. After a certain time at the levitation plane the AS leads the formation of clumps and their recirculation as clouds. When we shift by pulse mode, particles describes the pattern showed in Fig. 3b. We clearly demonstrate that pulse mode ultrasound can modify significantly the streaming velocity by keeping particles concentrated at the nodal plane. That means that it is possible for controlling/reducing the AS without switching off the **PRF**.

In pulse mode the AS can be reduced and the relaxation time increase by applying and modifying pulse mode factor. That means that the acoustic force is reduced in pulse mode. In this work, we performed experiments at different Pulse mode factors for different particle sizes and different resonator geometries. One of

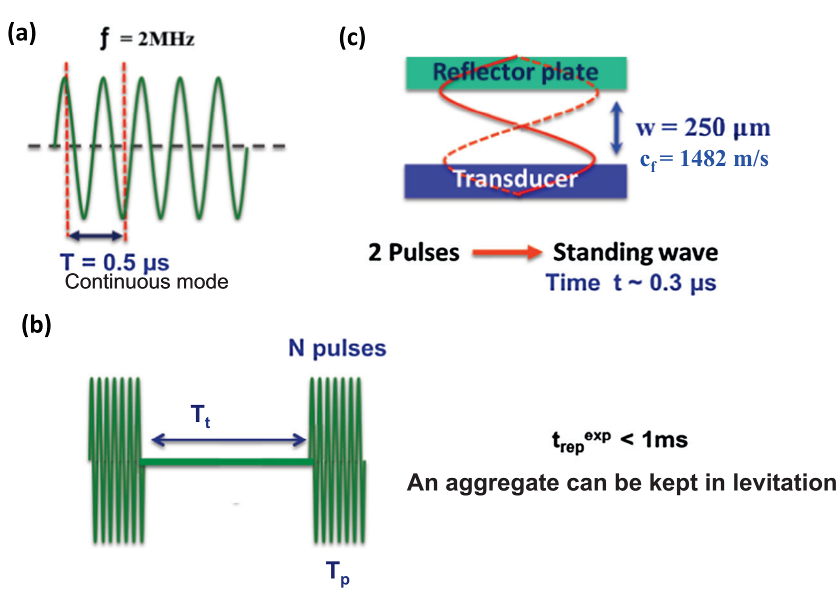

Fig. 2. (a) An USW of 2 MHz emitted in continuous mode. Each period of this wave lasts 0.5 μs. (b) In pulse mode acoustics, we send a burst of *n* pulses during a period time $Tp = n * f(-1)$ separated by a repetition time *Tt*. The *Tt* should be strong and long enough to maintain particles in levitation preventing sedimentation. Experimentally, we found a *Tt* of 1 ms as the minimum time in which particles can be kept in levitation. (c) For an acoustic resonator of 250 μm thickness por example, the minimum *n* to establish an USW is 2 pulses. The number of burst should be enough to generate the particles levitation but not enough for triggering the AS.