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# Varying the agglomeration position of particles in a micro-channel using Acoustic Radiation Force beyond the resonance condition

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ABSTRACT

It is well-known that particles can be focused at mid-height of a micro-channel using Acoustic Radiation Force (ARF) tuned at the resonance frequency ($h = \lambda/2$). The resonance condition is a strong limitation to the use of acoustophoresis (particles manipulation using acoustic force) in many applications. In this study we show that it is possible to focus the particles anywhere along the height of a micro-channel just by varying the acoustic frequency, in contradiction with the resonance condition. This result has been thoroughly checked experimentally. The different physical properties as well as wall materials have been changed. The wall materials is finally the only critical parameters. One of the specificity of the micro-channel is the thickness of the carrier and reflector layer. A preliminary analysis of the experimental results suggests that the acoustic focusing beyond the classic resonance condition can be explained in the framework of the multilayered resonator proposed by Hill [1]. Nevertheless, further numerical studies are needed in order to confirm and fully understand how the acoustic pressure node can be moved over the entire height of the micro channel by varying the acoustic frequency. Despite some uncertainties about the origin of the phenomenon, it is robust and can be used for improved acoustic sorting or manipulation of particles or biological cells in confined set-ups.



## 1. Introduction

The effects of an acoustic wave on suspensions have been observed for a long time [2,3]. Nowadays, it is well known that an acoustic standing wave applied to a suspension of particles can be responsible of mainly three phenomena: the Acoustic Radiation Force (ARF) [4], the acoustic streamings [5] and the Bjerknes forces [6]. All these effects can be observed in planar microfluidic devices using ultrasonic frequencies (typically in the hundreds of kHz to tens of MHz region). In this case, the micro-channels scales (from a few μm to a few hundreds μm) match well with the ultrasonic wavelengths. A special issue reviewing applications and theory of acoustofluidics in microfluidic systems for cell and particle manipulation has been recently published. Among other contributions, Bruus [7] presents the theory of the Acoustic Radiation Force responsible for the acoustophoretic motion of suspended micrometre-sized particles in an ultrasound field, while Wiklund et al. [8] detail how acoustic streamings can occur and be used for particle manipulation in microfluidic devices. Lenshof et al. [9], and Glynne-Jones et al. [10] give a very broad overview of rules and constraints to design and build properly microfluidic acoustic resonators.

From a theoretical point of view, the ARF is a force field generated because of the difference of acoustical properties between the bulk fluid and the suspension. It is a consequence of a non-linear effect in the time-average radiation pressure around an object in a sound wave. Many theoretical models have been proposed for the ARF. King [4] was the first to propose a theoretical expression for the forces on particles in a sound field, assuming particles as rigid spheres under acoustic plane wave, among other simplifying hypothesis. Yosioka and Kawasima [11] incorporated the compressibility of the particles in the modeling, while Gor'kov [12] proposed a model allowing the calculation of the acoustic force for an arbitrary acoustic field. Finally, Doinikov calculated the ARF for a viscous [13] and heat conductive [14,15] fluid. A complete review about the ARF is proposed by Groschl [16].

In our case, the model proposed by Yosioka and Kawasima [11], taking into account the compressibility of the particles, is a good approximation. It leads to the following expression for the ARF:

$$\langle \vec{F}_{ac_Y} \rangle = \frac{\pi}{4} \langle E_{ac} \rangle k d_p^3 F_Y \sin(2kz) \vec{e}_z \quad (1)$$

where $\langle\rangle$ denotes time averaging, $d_p$ is the particle diameter, $\langle E_{ac} \rangle$ is the acoustic energy density inside the channel, $k = \frac{2\pi}{\lambda}$ is the wave number of the acoustic plane wave of frequency $f$, $F_Y$ is the contrast factor, a positive (for polystyrene particles in water) numerical

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constant, and $z$ is the axial position of the particle, $z = 0$ being at the bottom of the channel and $z = h$ being at the top of the channel (Fig. 1).

If $\lambda = 2h$, then the ARF forces the particles to move towards the acoustic pressure node located at the mid-height of the channel ($z = h/2$). If the buoyancy force is negligible compared to the ARF, which is the case most of the time, then the mid-height of the half-wavelength channel is a stable equilibrium position where the particles gather. This phenomenon, also called acoustic focusing, is very useful and can be used in many applications such as micromanipulation of particles [17], filtering and recycling microbial cells [18], particle separation [19], improvement micro-PIV measurements and others [21].

Nevertheless, the fixed location of the pressure node is a strong limitation. In most of the applications cited above, it would be very interesting to move the particles elsewhere, or even to change dynamically the focusing location site. The hydrodynamic focusing [22] allows such flexibility on the focusing location, but it is an intrusive method, which can not be used in many situations.

There have been many attempts trying to change the location of the acoustic pressure node for improved particle manipulation in microfluidic devices. For instance, considering a multilayer resonator and choosing properly the carrier layer and reflector thicknesses, the pressure node position for a single half-wavelength resonant channel can be moved elsewhere than the mid-height of the channel [1,23]. A strong limitation of this approach is that the location of the pressure node remains fixed for a given channel geometry and given wall materials. Finding a solution to change the focusing position without building a new device would be a significant gain in these types of systems.

Actually, it is possible to change or move the pressure node location without altering the micro-channel. Haake [17] achieved to move the pressure node location in a configuration with two identical transducers on each side of the micro-channel, changing the phase or magnitude of one of the transducers. However, the efficiency of the acoustic focusing was strongly reduced while changing the position of the pressure node.

Lipkens et al. [24] demonstrated that it is possible to achieve particle translation along the axial direction through a periodic sweeping of the excitation frequency. The frequency is changed in time to various resonance frequencies, changing the number of pressure nodes in the resonator and their locations, creating a controlled motion along the axial direction. Using this technique, it is possible to move particles but it is not possible to focus the particles on a new stable axial position.

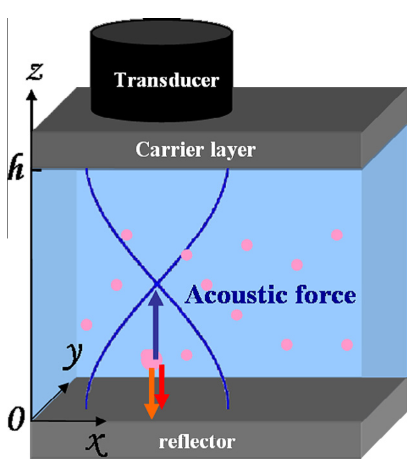


**Fig. 1.** Forces applied on a particle in still water and in standing acoustic wave. The acoustic force applied on the particle is always directed towards the acoustic pressure node.

Glynne-Jones et al. [25] found a way to move the focusing location wherever they want in one half of the channel by alternating between the half-wave mode (stable equilibrium position located at mid-height), and the quarter-wave mode (stable equilibrium position located at the top of the channel). By choosing properly the ratio and the frequency of the switching, the resulting stable equilibrium position can be set everywhere between the mid-height and the top of the channel. However, only one half of the channel can be explored, and the focusing velocity is significantly decreased for the intermediate positions.

In the following, we will show that it is possible to move the particles along the entire height of a micro-channel and to keep them on new stable focusing locations using ARF.

## 2. Experimental set-up

### 2.1. Micro-channel and optical set-up

The experiments have been carried out in a micro-channel (Fig. 1) made of a carrier layer (upper wall) and a reflector (lower wall). Both walls are 1 mm thick and can be made either of PMMA (Polymethyl methacrylate) or glass. The side-walls and design of the micro-channel are cut into a 337 μm thick mylar sheet which is the height of the reference PMMA–PMMA channel (upper and lower walls made of PMMA). The micro-channel is 10 mm wide and 40 mm long.

Observations were made using a standard micro-PIV setup [20,26] with a 15 Hz pulsed Nd:YaG laser and a filter cube with a narrow filter band around $\lambda_{fcube} \approx 612$ nm (Fig. 2). The fluorescent micro-beads (Thermo Scientific®) have an absorption wavelength $\lambda_a \approx 542$ nm and an emission wavelength $\lambda_e \approx 612$ nm for a diameter $d_p = 7$ μm. Images are recorded by a 12 bits LaVision ® Imager Pro Plus double frame camera (1600 × 1200 pixels).

The micro-channel is set on a fully motorized 3-axis microscope stage. The Zeiss® objective has a magnification $M = 10$, a numerical aperture $NA = 0.3$ and a focal length $F = 5.1$ mm.

### 2.2. Acoustic set-up and parameters

A plane acoustic standing wave field is established through the superposition of two waves of equal wavelength and magnitude traveling in opposite directions along the height of the micro-channel. Instead of using two transducers on both sides of the channel, which would prevent us from exploring the area between them with the micro-PIV system, we use a single transducer on the upper wall, the opposite wave being the wave reflected on the lower wall.

A 7 mm diameter cylindrical piezoelectric transducer from Signal processing® is fixed on the upper wall of the channel (Fig. 1) using a layer of ultrasonic gel to ensure the coupling between the transducer and the upper wall of the channel. Its functional frequency is approximatively $f = 2$ MHz. In order to obtain a single pressure node in the channel, the acoustic wavelength must be twice the channel height. The acoustic frequency is then tuned to match the condition $\lambda = 2h$ i.e. $f \approx 1.91$ MHz. The peak-to-peak voltage $U_{pp}$ applied to the transducer is the parameter used to control the magnitude of the acoustic force. It is proportional to the acoustic velocity magnitude and it ranges between 1 to 10 V as usual for this kind of application (cf special issue of Bruus et al. [27]).

As the objective of these experiments is to study the influence of the acoustic frequency on acoustic focusing over a large frequency range, it was important to use a wide-band acoustic transducer. In this case, the frequency of the transducer ranges between 1 MHz and 3 MHz. It is different from the transducers