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Y-shaped jets driven by an ultrasonic beam reflecting on a wall

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ABSTRACT

This paper presents an original experimental and numerical investigation of acoustic streaming driven by an acoustic beam reflecting on a wall. The water experiment features a 2 MHz acoustic beam totally reflecting on one of the tank glass walls. The velocity field in the plane containing the incident and reflected beam axes is investigated using Particle Image Velocimetry (PIV). It exhibits an original y-shaped structure: the impinging jet driven by the incident beam is continued by a wall jet, and a second jet is driven by the reflected beam, making an angle with the impinging jet. The flow is also numerically modeled as that of an incompressible fluid undergoing a volumetric acoustic force. This is a classical approach, but the complexity of the acoustic field in the reflection zone, however, makes it difficult to derive an exact force field in this area. Several approximations are thus tested; we show that the observed velocity field only weakly depends on the approximation used in this small region. The numerical model results are in good agreement with the experimental results. The spreading of the jets around their impingement points and the creeping of the wall jets along the walls are observed to allow the interaction of the flow with a large wall surface, which can even extend to the corners of the tank; this could be an interesting feature for applications requiring efficient heat and mass transfer at the wall. More fundamentally, the velocity field is shown to have both similarities and differences with the velocity field in a classical centered acoustic streaming jet. In particular its magnitude exhibits a fairly good agreement with a formerly derived scaling law based on the balance of the acoustic forcing with the inertia due to the flow acceleration along the beam axis.

1. Introduction

Acoustic streaming designates the ability to drive quasi-steady flows by acoustic propagation in dissipative fluids and results from an acousto-hydrodynamics coupling. Nyborg [1] and Lighthill [2] gave a theoretical insight into this phenomenon in the case of acoustic waves propagating in an infinite medium. In particular, they have shown that these flows can be modeled as those of incompressible fluids driven by a volumetric acoustic force f_{ac} given by:

$$\vec{f}_{ac} = \frac{2\alpha}{c} I_{ac} \vec{x}', \tag{1}$$

where α is the acoustic pressure wave attenuation coefficient, c is the sound celerity, I_{ac} is the temporal averaged acoustic intensity and $\vec{x}'$ is the direction of acoustic waves propagation.

The use of Eq. (1) in the incompressible Navier–Stokes equations has been validated by several experimental investigations [3–9].

They have been conducted in the so-called Eckart configuration, that is to say a situation featuring progressive acoustic waves far from walls, in order to avoid as much as possible interactions with walls. This method leads to two main results which confirm the reliability of the approach. Firstly, a linear acoustic model is suitable and convenient to compute the spatial variations of the force term given by Eq. (1) [8,9]. Secondly, scaling laws for the flow velocity are found to be consistent with the obtained experimental results [8].

Acoustic streaming can significantly affect heat and mass transfer in a great number of processes, and even lead to turbulent mixing. An extensive review of all the processes in which acoustic streaming could bring significant improvements is outside the scope of the present paper; let us just mention that such a review should include biomedical applications [10–14], sonochemistry [15–18], acoustic velocimetry [19] and even semi-conducting

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crystals growth and metallic alloys solidification [20–31]. The fluids involved in these processes may of course have very different acoustical and mechanical properties; but a proper dimensional analysis approach can be used to deduce from water experiments a quantification of the flow which would be observed in any other Newtonian fluid [8]. Another peculiarity of applications is that they are generally implemented in a finite size, more or less confined, domain; a limitation of the former experimental investigations with respect to this confinement is that they generally feature an absorbing wall facing the acoustic source to prevent reflection of the acoustic waves. Setting such nearly ideal boundary condition is usually not possible in the applications cited above, so that accounting for acoustic reflections is now a key issue in the modeling of such applications.

The present study is thus dedicated to the experimental investigation and numerical modeling of the acoustic streaming flow generated in water by an ultrasonic beam reflecting on a wall. The ASTRID experimental setup (Acoustic STReaming Investigation Device) used in our previous studies [7–9] has been adapted for the present investigation. A challenge in the modeling is, in particular, to deal with the complexity of the acoustic field in the area of the reflection, close to the wall, where the waves are neither plane nor even with a very clear propagation direction. Besides the modeling issues, this is, as far as we know, the first report of an acoustic streaming flow generated by a reflecting acoustic beam and a yet unobserved and original flow pattern is put into light.

The experimental setup will be described in Section 2, the modeling strategy, in Section 3, and the results and the discussion will be presented in Section 4.

2. Experimental setup and typical flow pattern

Experiments are performed in a rectangular cavity filled with water. A top view of the setup is presented in Fig. 1; this is actually a modification of the formerly presented ASTRID setup [7–9]. A 2 MHz circular plane transducer from *Imasonic*™, with a diameter of 29 mm, is used to generate the acoustic beam. The investigation domain is delimited by two sound absorbing plates made of Apflex F28 tiles from *Precision Acoustics*™. The first plate (from left to right on Fig. 1) is positioned close to the transducer. It is drilled with a 63 mm hole and covered with a thermo retractable plastic film to let the sound enter in the investigation area but, at the same time, provide a rigid wall condition for the generated steady flow. The second plate is the end-wall of the investigated area. In our former studies [7–9], the distance between the centers of the transducer surface and the plastic film was 10 mm and the second plate was set at 275 mm from the transducer surface center. In the present

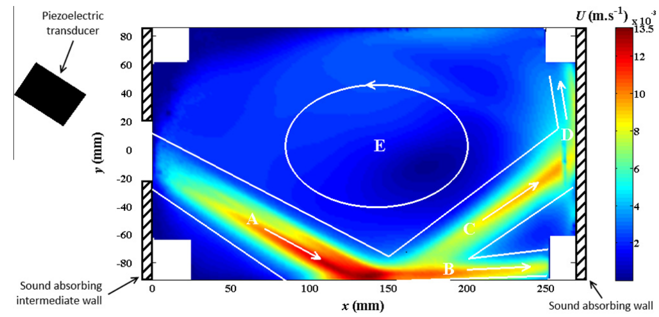

Fig. 2. Velocity magnitude obtained by PIV in the *xy* horizontal plane for an electrical power of $P = 8$ W. The piezoelectric transducer and the two absorbing walls are also represented as in Fig. 1. Four fastening systems, used to maintain the top wall, mask little zones at each corner, which appear as white squares. The observed "y-shaped" flow pattern is underscored by white lines. We distinguish 5 elements in the structure of this flow: A (incident acoustic streaming jet), B (first wall jet), C (reflected acoustic streaming jet), D (a second wall jet at the end-wall) and E (large recirculation at the scale of the cavity).

study, the positions of the film and plates are kept identical, but the transducer is displaced. A glass lid is moreover installed on top of the water in order to avoid the dissymmetry in the boundary conditions due to a free surface. The dimensions of the investigation volume delimited by the two sound absorbing plates and the side, top and bottom walls of the glass tank are thus $265 \times 180 \times 160$ mm^3 (length × width × depth).

As depicted in Fig. 1, the transducer is tilted from its original position along the tank axis so that it is now oriented toward a side wall and creates a beam in the middle horizontal *xy* plane (namely at 80 mm from the bottom and top walls). Note that the origin of the (x,y,z) frame is set at the center of the drilled hole in the intermediate absorbing plate. This acoustic beam impinges at the middle of the side wall with an angle $\beta = 34°$; it is then reflected toward the end-wall where it is absorbed (Fig. 1).

A PIV (Particle Image Velocimetry) system is used to measure the velocity field in the horizontal middle *xy* plane for three electrical powers: $P = 2$, 4 and 8 W. It includes a continuous laser which emits light at a wavelength of 532 nm. Image acquisition is performed with a camera from *Stemmer Imaging*™ with a resolution of 2048×2048 pixels typically operated in single frame mode at a 5 frames per second regular rate. The post-treatment is performed using *Davis*™, the software by *Lavision*. A multi-pass approach is used with final *Interrogation Areas* (*IA*) of size 16×16 pixels^2 and an overlap of 50% between neighboring *IA*; as a consequence the velocity fields is obtained on a grid of typical mesh-size 1.3 mm, which is comparable to the 1 mm mesh-size

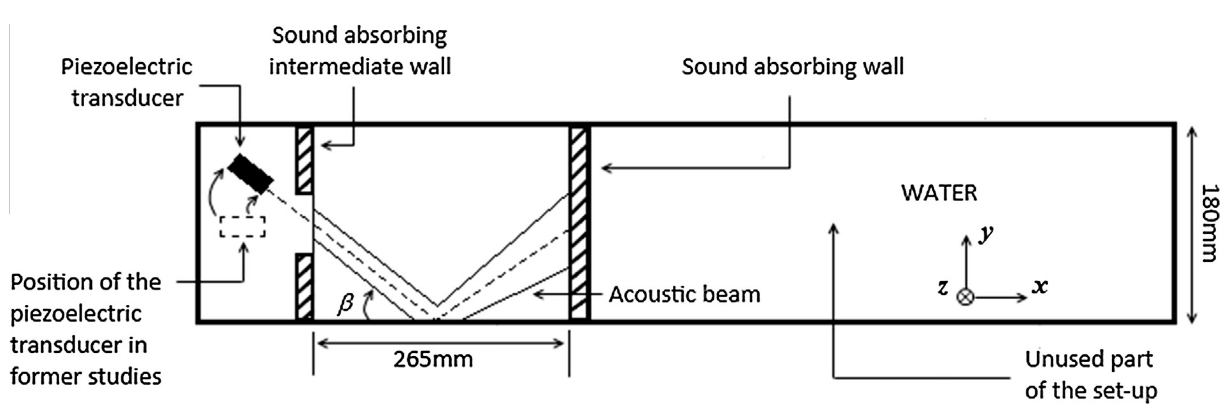

Fig. 1. Experimental setup (top view). The origin of the Cartesian frame is set at the middle of the inner surface of the sound absorbing intermediate wall: *x*-axis is parallel to the lateral walls, *y* and *z* axis are respectively horizontal and vertical. The depth is 160 mm and a glass lid avoids the presence of a free surface.