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Experimental and theoretical investigation of microstreaming generated by a cavitation bubble undergoing nonspherical oscillations

Gabriel Regnault^{1,2}, Alexander A. Doinikov¹, Sarah Cleve^{1,2}, Cyril Mauger¹, Philippe Blanc-Benon¹, Claude Inserra²

¹*Univ Lyon, École Centrale de Lyon, INSA Lyon, Université Claude Bernard Lyon 1, CNRS, LMFA, UMR 5509, France*

²*Univ Lyon, Université Claude Bernard Lyon 1, Centre Léon Bérard, INSERM, UMR 1032, LabTAU, France*

Abstract

A microbubble of a given size and submitted to an acoustic field may undergo axisymmetric nonspherical oscillations for sufficiently large acoustic amplitudes. These nonspherical oscillations, in addition to the radial and possibly translational oscillations, will generate in the bubble vicinity a flow called microstreaming. Cavitation microstreaming is of peculiar importance in engineering (micromixing) and biomedical fields (shear stress applied to cell and tissues). A current challenge is to predict and control the microstreaming pattern and velocity field induced by a bubble with known oscillatory dynamics.

Keywords

Ultrasonics, microbubble, microstreaming

I. Introduction

Microstreaming is a slow mean flow generated in the vicinity of an oscillating bubble. It creates in the bubble direct environment shear stress that can be used for different applications in biomedical (sonoporation effect) and engineering fields (micromixing). Theoretical studies have been developed to explain this phenomenon in the case of a free bubble in an unbounded fluid^[1,2], while experimental investigation are limited to the case of a bubble attached to a solid boundary has been investigated^[3]. Previous experimental and theoretical works have shown that this microstreaming is initiated due to the presence of nonspherical modes in the bubble oscillation. These modes can be translational motion or nonspherical distortion of the bubble interface. The present study focuses on the case of nonspherical axisymmetric deformations, also called “shape modes”, and their influence on microstreaming from both experimental and analytical point of view. More particularly, this work aims at validating a recently developed model of microstreaming generated by a free bubble undergoing axisymmetric oscillations^[4] by comparison with experimental measurement.

In the case of monochromatic excitation, the triggering of the shape modes requires to exceed a certain threshold in a pressure/radius space^[5,6]. Depending on the size of the bubble different shape modes can be induced. A common method to trigger the instabilities is to increase the pressure until the desired threshold is reached. However, this technique does not offer a full control of the oscillation, and in particular it can cause the apparition of erratic motion of the bubble. Another technique called coalescence^[7], used for the present investigations, enables to ensure the establishment of a steady-state regime of the oscillations and to control the axis of symmetry of the non-spherically oscillating bubble. This last point is of main interest because it allows obtaining 3D information from 2D imaging on the bubble oscillations, if the axis of symmetry is contained within the plane of observation. The symmetry of the bubble is extended to the microstreaming, which can then also be fully characterized by 2D imaging.

II. Methodology

An experimental setup has been designed such as both the bubble dynamics and its associated microstreaming can be measured. The bubble dynamics is required as the interface motion is at the origin of the fluid motion, but also as input data (amplitude, phase and frequency of the oscillating shape modes) of the proposed theoretical model^[4].

The shape mode oscillations are triggered using the coalescence technique. First a bubble is created by focusing the second harmonic of a Nd: YAG pulsed laser ($\lambda = 532$ nm NewWave Solo PIVIII) in a cubic tank (of 8cm-side), filled with filtered water for the present study. This bubble is trapped on a pressure antinode of an acoustic standing wave (31.25 kHz) created using a Langevin (Reson[®], 31 kHz nominal frequency) transducer. Another bubble is then generated using the same laser, and migrates to the same anti-node. The two bubbles merge into a single one. The resulting bubble is bigger and under sufficient acoustic amplitude, may exhibit non spherical oscillations. The axis of symmetry of the non-spherically oscillating bubble is identical to the rectilinear translational motion of the two approaching bubbles before impact^[7], and can be controlled experimentally. The nucleation of bubbles using a focused laser does not offer a complete control on the bubble size. However, the energy of the laser beam can be tuned to create bubble with radii ranging between 20 μm and 40 μm . The bubble is observed using backlight imaging, with a high-speed camera (180 kfps) Phantom V12.1 VisionResearch, whose focus plane contains the axis of symmetry of the bubble. This set-up gives then all the 3D information of the studied case, with 2D imaging. The fluid is characterized using seeding particles: a continuous wave laser (CNI 400 mW, 532 nm) coupled to a cylindrical lenses forms a laser sheet with a thickness of about 200 μm . The laser sheet illuminates dyed red fluorescent particles (R700 ThermoFisher, 0.71 μm in diameter) whose size is small enough to accurately follow the flow. Motion of the particles is captured by the high-speed camera with 2000 Hz acquisition rate. The visualization allows characterizing almost instantaneously the dynamics of the bubble and the generated microstreaming. The full setup is shown in figure 1.

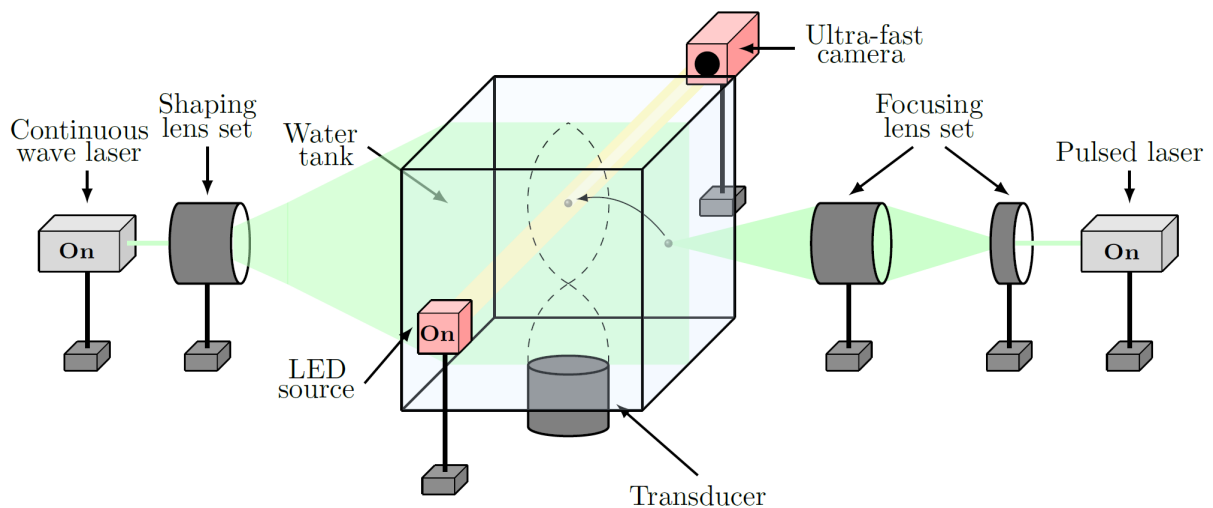


Figure 1: Experimental setup for bubble dynamics and microstreaming measurement.

In addition, we derive a theoretical model of microstreaming produced by a non-spherically oscillating bubble. According to this theory, microstreaming is generated due to the interaction between two modes oscillating at the same frequency. No restrictions are imposed on the ratio of the bubble radius to the viscous penetration depth (i.e. no restrictions on the bubble size and on the fluid viscosity). Let us refer by $n = 0$ to the breathing (spherical) mode, $n = 1$ to the translation motion and $n = 2, 3, \dots$ to the surface modes. Two

kinds of contribution can exist: a mode with another one (case $n-m$) or a mode generating microstreaming by itself (case $n-n$). For the last one, the order of the mode n must be at least equal to 1, since the breathing mode alone does not generate microstreaming. At this stage, only two particular interacting cases have been fully derived: the case $0-m$ and the case $n-n$ ^[4]. The most general case $n-m$ cannot yet be taken into account in the following simulations. The size of the bubble and the modes characteristics (amplitudes, frequency, phase) are extracted from the experimental observations. These parameters are given as input data to the model along with the fluid properties (viscosity, density, surface tension).

In the experimental and numerical analysis, both the velocity field and the pattern of microstreaming can be quantified. In the following section is shown a first qualitative comparison between an experimental result and the corresponding numerical simulation.

III. Results and discussion

The studied case is a bubble of $47\ \mu\text{m}$ oscillating on a mode 2. The modal amplitudes are obtained by projection of the bubble interface contour on the Legendre polynomials basis, a sub-graph of the spherical harmonics due to the axisymmetric properties:

$$r_s = R_0 + \sum_{n=0}^N a_n e^{-i2\pi f_n t} P_n(\mu) \quad ,$$

where r_s is the instantaneous radius of the bubble, R_0 is the radius at rest, f_n is the oscillating frequency, P_n is a Legendre polynomial of order n and $\mu = \cos \vartheta$, where ϑ refers to the angular polar coordinate of the bubble interface. The experimental modal decomposition is shown in figure 2.a).

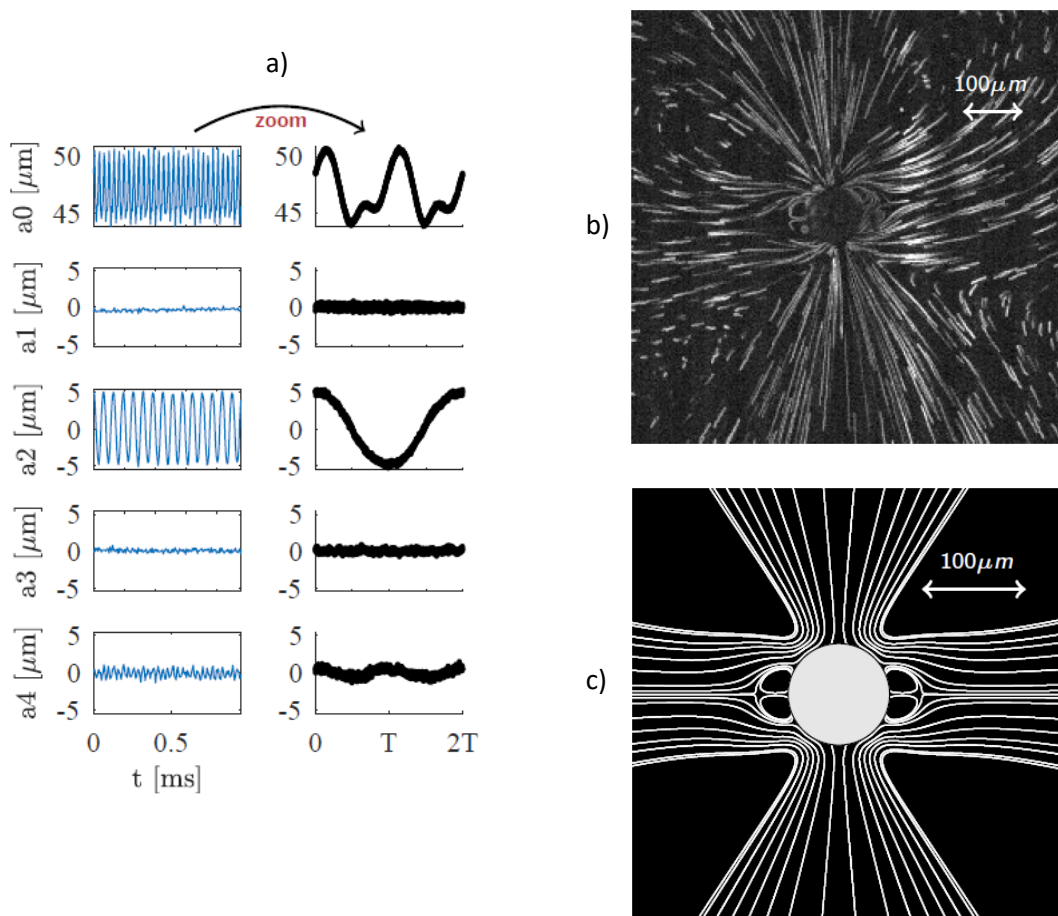


Figure 2: Case of a bubble of $47\ \mu\text{m}$ oscillating on a mode 2, submitted to about 20 kPa.
a) Modal decomposition, b) Experimental streaming, c) numerical streaming.

The right column of figure 2.a) shows a focus on two acoustic period of the studied oscillations. Three modes are present in this case: the breathing mode, the mode 2 and the mode 4. The instability triggered in this case is the mode 2 oscillating at half the excitation frequency. The mode 4 is of relatively low amplitudes, oscillates at the excitation frequency, and is only present due to nonlinear coupling between modes^[8]. A spectral analysis on the mode 0 indicates the presence of two components, one at the fundamental ($f = f_0 = 31.25$ kHz) and another at its first harmonic ($f = 2f_0$). According to the theory, three interactions can exist for this case: the mode 2 with itself at $f_0/2$, the mode 4 with itself at f_0 and the mode 0 with the mode 4 also at f_0 . The experimental and numerical pattern are given in figure 2.b) and 2.c). Both of them present identical patterns. They consist in a large cross with small 4 zones of recirculation close to the bubble, organized by pair. The recirculation zones are comparable in size for the two cases.

The global pattern shown here corresponds to the one obtained for a mode 2 alone. It is predominant here due to the high amplitude of the mode 2, in comparison with the mode 4 (self-interaction 4-4 or with the radial mode 0-4). For this case, the influence of the interactions 0-4 and 4-4 is then shown to be negligible. Nevertheless, care has to be taken in the interpretation of the effect of the modal amplitude as a low amplitude is not necessary correlated to a low intensity microstreaming field. Indeed, phase shift between modes has to be considered as it may intensify by many times the velocity field^[4].

IV. Conclusion

Both experimental and theoretical streaming are presented in this document. They are correlated with experimental bubble oscillation made just before the flow measurement. The case presented here confirms at first sight the analytical model. Particular characteristics such as the recirculation zones are found numerically, which consolidates the theory. If validated with other experimental cases and with quantitative velocity fields, the model will be a great asset to understand the influence of fluid properties and bubble size on microstreaming.

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