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Experimental investigation of microstreaming induced by free nonspherically oscillating microbubbles

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Microbubbles exposed to a sufficiently strong ultrasound field can show nonspherical oscillations called surface modes. In the vicinity of the bubble surface, these oscillations induce a slow mean flow named microstreaming. Microstreaming plays an important role in medical applications such as sonoporation as well as in engineering applications such as micromixing. A better understanding of the induced flows will hence be beneficial to a large number of applications. Recent studies mainly report on microstreaming induced by bubbles resting on a solid boundary. The observation of microstreaming around a single, free bubble is challenging, because several experimental difficulties have to be overcome: Avoidance of translational instabilities, obtainment of a steady-state behavior maintaining surface modes, correct choice of tracer particles, and correlation between fast temporal bubble dynamics and relatively slow microstreaming. We present an experimental setup, that accomplishes the simultaneous visualization of microstreaming and bubble dynamics. Different streaming patterns can be observed.

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INTRODUCTION

An oscillating cavitation bubble can set the surrounding fluid into motion, a phenomenon called microstreaming. Most experimental studies on cavitation-induced streaming flows focus on bubbles resting on solid boundaries[1] as this facilitates the control of the bubble size and bubble location, as well as fluid motion observation. For such bubbles, it has been observed that streaming velocities undergoing shape oscillations are much larger than the velocities induced by bubbles with radial oscillating and translational motion.[2] The main drawback with bubbles resting on a solid boundary is the assessment of the bubble dynamics, usually empirically determined due to the huge complexity of the contact line dynamics leading to nontrivial interaction of shape and volume oscillations.[3] While these conditions are of interest for microfluidic transport applications, therapeutic microbubbles are usually free in the liquid. For free bubbles, nonspherical oscillation dynamics has been widely studied theoretically,[4,5] and is experimentally studied even for strong acoustic pressure where nonlinear interactions between modes occur.[6] Moreover, all theoretical developments on microstreaming patterns consider oscillating microbubbles in infinite liquid.[7–9] In the present study an experimental technique is presented for the achievement of controlled microstreaming of a free, nonspherically oscillating microbubble.[10] Bubble coalescence technique is used to trigger surface modes of trapped microbubbles. This technique leads to steady-state oscillations of a given shape mode over a sufficiently long time scale, allowing the tracking of fluid motion with tracer particles. Streaming patterns are obtained and their appearance can be correlated to the parametrically excited surface modes.

EXPERIMENTAL SETUP

A schematic drawing of the experimental setup and its different operational modes is presented in Fig. 1. Experiments are conducted in an 8-cm-edge cubic water tank filled with bidistilled undegassed water. A standing ultrasound field is created by an ultrasonic plane transducer (SinapTec®, diameter of the active area $35\,\mathrm{mm}$), which is attached to the bottom of the tank. The voltage amplitude of the transducer is varied between 1 and $10\,\mathrm{V}$, no gain amplifier is used. The driving frequency is set to $31.25\,\mathrm{kHz}$ for all experiments, corresponding to a resonant radius $R_{res} \approx 104\,\mu\mathrm{m}$ according to Minnaert's theory.[11] All bubbles studied in the current work are below resonant size and will be driven towards pressure antinodes due to primary Bjerknes forces. Single bubbles are nucleated by short laser pulses ($\lambda = 532\,\mathrm{nm}$, second harmonic of a Nd:YAG pulsed laser, New Wave Solo III, $6\,\mathrm{ns}$ pulse duration). Experiments are captured with a CMOS camera (Vision Research® V12.1) equipped with a $12\times$ objective lens (Navitar®). It is pos-

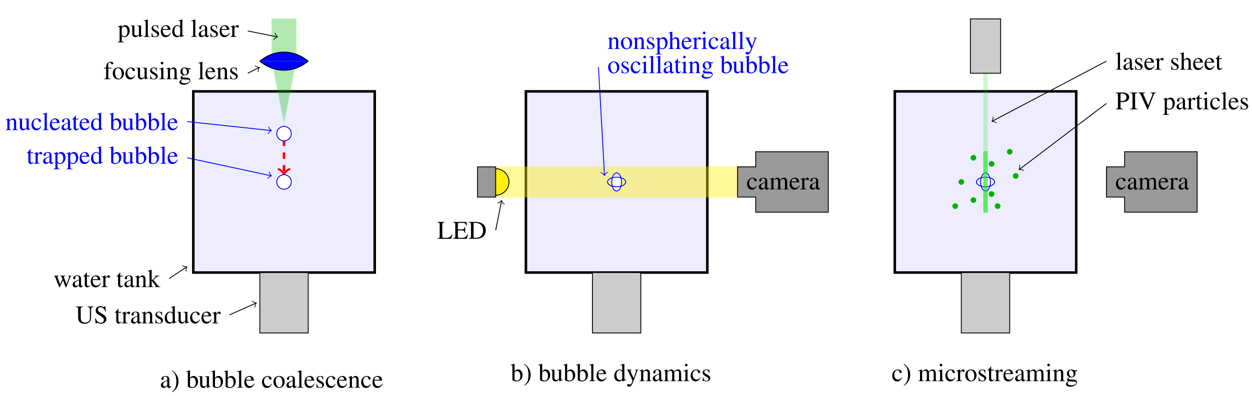

Figure 1: Experimental setup using the following steps: a) triggering of surface modes by bubble coalescence, b) recording of the bubble dynamics, c) recording of the microstreaming.

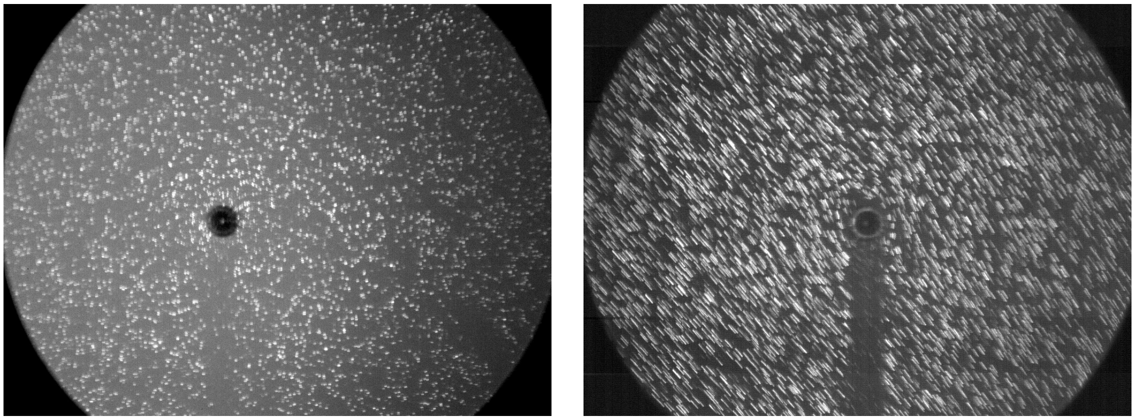

Figure 2: Fluorescent tracer particles around two bubbles oscillating in a purely spherical mode. Both images correspond to a superposition of 100 snapshots covering 0.25 s. Left: No motion of the tracer particles can be observed. Right: A parasite mean flow can be observed in the whole image. However, this flow is not linked to the bubble motion.

sible to switch between two operating states: bubble dynamics and microstreaming. For the visualization of the bubble dynamics, backlight illumination with a light-emitting diode (LED) is used. A frame size of $256 \times 256\,\mathrm{pixels}$ and a frame rate of $67.065\,\mathrm{kHz}$ are chosen. For the visualization of microstreaming, red fluorescent polymer microspheres (diameter, $0.71\,\mu\mathrm{m}$, Duke Scientific) are added. The particles are illuminated by a continuous thin laser sheet ($\lambda = 532\,\mathrm{nm}$). A frame size of $1024 \times 768\,\mathrm{pixels}$ and a frame rate of $400\,\mathrm{Hz}$ are chosen. A fast switch between the two operating states allows for information on bubble dynamics as well as microstreaming.

ENSURING LONG-TIME STABLE NONSPHERICAL OSCILLATIONS

One of the main difficulties when assessing microstreaming induced by a free bubble is to keep the nonspherically oscillating bubble in a steady-state regime over a sufficiently long time. In order to meet this requirement, bubble coalescence is used to trigger surface modes:[10] two bubbles encounter each other and merge into a new single one of equilibrium radius R_e. Depending on R_e different surface modes n of natural frequency $\omega^2 = (n-1)(n+1)(n+2)\sigma/(\rho R_e^3)$ can be triggered if the applied acoustic pressure exceeds the parametric threshold of the n^{th} mode. Furthermore, bubble coalescence technique enables the control of the axis of symmetry which rules the oscillations of the bubble on the zonal spherical harmonics. The bubble interface is then described by the coordinate $r_s(\theta, t) = R(t) + \sum_{n=2}^{\infty} a_n(t) P_n(\cos(\theta))$, where $R(t)$ stands for the volume mode amplitude, $a_n(t)$ for the respective surface mode amplitude of the mode n, and P_n denotes the Legendre polynomial of order n. By ensuring axisymmetric nonpsherical oscillations, and by placing the axis of symmetry in the focal plane of the camera, we can hence observe the bubble and its associated streaming, which are 3D phenomena, in the 2D focal plane of the camera without bias.

EXAMPLE OF BUBBLE DYNAMICS AND MICROSTREAMING RECORDING

When two bubbles coalesce at a given pressure amplitude below the parametric threshold, only spherical oscillations remain and no effect on the surrounding fluid is observed (see Fig. 2, left). Under certain circumstances, an overall mean flow can be observed, see Fig. 2 on the right. This flow is however not linked to the bubble motion, as it appears even without the presence of a bubble. Possible reasons are the remaining inertial effects of the water introduced in the tank and buoyancy forces due to the heating of the

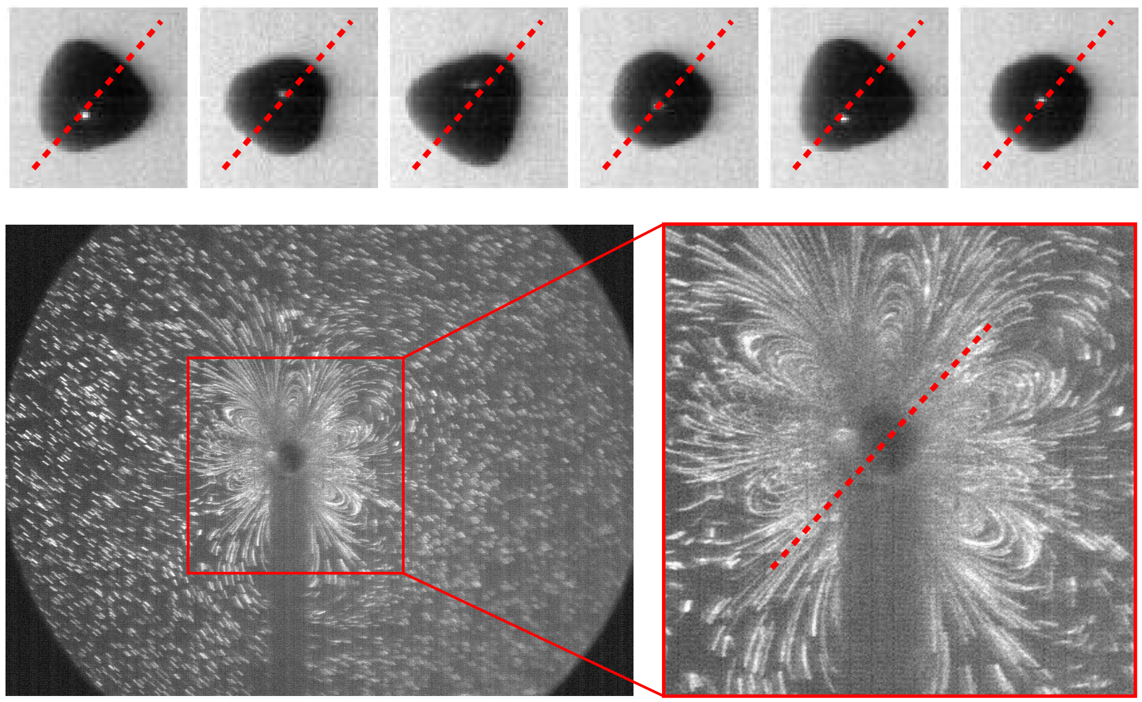

***Figure 3:** Above: Bubble dynamics of bubble oscillating in a mode 3, represented by consecutive snapshots over two acoustic periods (0.064 ms). The axis of symmetry is indicated by the dashed red line. Below: Streaming pattern induced by this bubble. The image corresponds to a superposition of 100 snapshots covering 0.25 s. The width and height of the red box are 0.7 mm.*

laser sheet. As streaming is a relatively slow effect, care has to be taken that no too strong influence of the parasite background flow appears.

Microstreaming only appears when translational or nonspherical oscillations occur in addition to the volume oscillations. Several recordings of nonspherically oscillating bubbles generated by coalescence have been made. An exemplary result is shown in Fig. 3 for a $70\,\mu\mathrm{m}$ radius bubble in a $15\,\mathrm{kPa}$ ultrasound field, thus above the parametric threshold amplitude of $8\,\mathrm{kPa}$ for the $n = 3$ surface mode. Consecutive snapshots on the bubble dynamics on two acoustic periods reveal the subharmonic behavior for nonspherical oscillations. When looking at the induced microstreaming pattern, the trajectories of the particles can be visualized by streak photography (Fig. 3). All trajectories together form a steady streaming pattern. In the presented case, six lobes can be distinguished in agreement with the multipole radiation of the $n = 3$ surface mode. The correlation between the microstreaming pattern and the bubble dynamics is ensured by capturing bubble dynamics before and after tracking of particle motion. In particular, this can allow correlating the microstreaming velocities to the surface mode amplitudes. A detailed discussion is however beyond the scope of the present paper. To obtain the streaming velocities, particle image velocimetry can be used. For the surface mode amplitudes of the nonspherical oscillations, a modal decomposition over the Legendre polynomials taking into account the axis of symmetry as depicted in Fig. 3 is needed.

CONCLUSION

A setup and exemplary results of microstreaming around nonspherically oscillating bubbles are presented. By taking advantage of bubble coalescence in a standing ultrasound field, long-time stable nonspherical oscillations of microbubbles are obtained. Successive recordings of fluid tracers motion and oscillations of the acoustic time scale allows associating streaming patterns to the corresponding bubble dynamics.

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