Optic cavitation in an ultrasonic sound field

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Introduction

The dynamics and luminescence of transient bubbles produced by nanosecond laser pulses has been studied extensively (e.g., see [1] and references therein). These bubbles grow to a maximum radius of a few millimeters and then collapse, sending a flash of light at the time of maximum compression. Ohl [2] has shown that luminescence of such bubbles can be enhanced or reduced by a continuous sound field in the cuvette. To achieve strong response of the bubbles the sound frequency should be around or below their resonance frequency. With large laser-generated bubbles, frequencies are too low to be coupled efficiently in the small cuvettes used in optical cavitation. Thus, in this work we want to analyze the behavior of small bubbles that can be obtained by femtosecond laser pulses in an ultrasonic sound field. Due to the nonlinear effect of self focusing, these bubbles are not spherical. In studies of Geisler [3], no luminescence could be found in the absence of a sound field for these elongated bubbles. The idea of the present work is to boost the collapse of such bubbles by sound in order to get cavitation luminescence.

Methods

A mode-locked Ti:Sapphire laser system is used to generate laser pulses of 130 fs duration and 0.5 μJ pulse energy. These are focused into the center of a water-filled cuvette. In order to get a relatively small plasma to seed a small bubble, the optics was optimized to have small spherical aberration. The cuvette is insonicated at its resonance frequency of about 44.56 kHz by a piezoceramic transducer glued at the bottom. To get a broader resonance, the cuvette is clamped between two pieces of hard rubber that damp the acoustic standing-wave field. The sound generator and the laser electronics are synchronized to be able to generate bubbles at well defined, adjustable phases of the acoustic cycle. For photography, the bubbles are illuminated by a xenon flash lamp and observed through a long distance microscope mounted on a fast CCD camera (200 ns exposure time). The camera system is also synchronized with the laser and sound generator. An adjustable delay between the laser breakdown and the exposure of the camera permits to take pictures of the bubble at different times of the collapse cycle. Although every picture comes from a different bubble, due to their good reproducibility an image sequence can be generated showing the bubble dynamics. Alternatively, the bubbles are observed by a photomultiplier (PMT) to detect possible cavitation luminescence. The photomultiplier is cooled down to -20° C to reduce noise and is protected from laser radiation by a dielectric mirror.

To estimate the parameters of observed bubbles, their dynamics is compared with numerical solutions of the Gilmore model [4] for spherical bubbles. This is done by measuring the bubble volume to get an equivalent spherical dynamics. The Gilmore model is of first order in the Mach number and incorporates compressibility effects, the viscosity and the surface tension of the liquid. We used the Van der Waals hard-core law for the water vapor in the bubble. In the following R denotes the bubble radius and R_m its equilibrium radius; p_{ac} is the ampiltude of the sinusoidal standing wave field in the cuvette.

Results and Conclusion

The bubble parameter R_m and initial conditions $(R(0), \dot{R}(0))$ should be independent of sound pressure amplitude and only be determined by the shape and energy deposit of the laser plasma. While $R(0) = 4.87\ \mu$m could be measured directly from the images, R_m and $\dot{R}(0)$ were obtained indirectly by least-squares fitting of numerical solutions of the model, giving $R_m = 3.2\ \mu$m and $\dot{R}(0) = 49.3$ m/s for the experiment presented here. The acoustic pressure p_{ac} could not be measured reliably by available hydrophones because they disturbed the resonance. Therefore, least-squares fitting with respect to the collapse time was used again for the acoustically excited bubble, adjusting p_{ac} and phase ϕ of the sound field to give minimum deviation, yielding $p_{ac} = 146$ kPa (see Figure 1). The photomultiplier signal was recorded from 0.8 μs to 23.44 μs after breakdown covering one acoustic period.

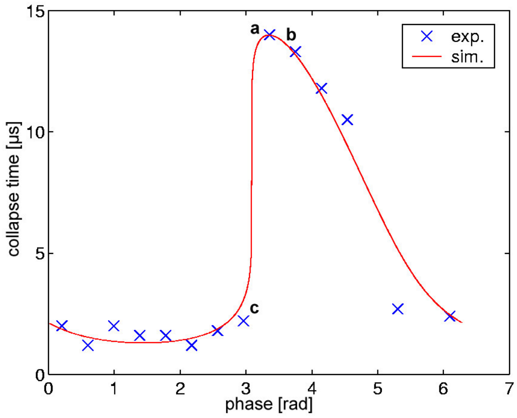

Figure 1: Collapse time of a bubble in a sound field as a function of seeding phase, with $p_{ac} = 146$ kPa, $f_{ac} = 44.56$ kHz, R(0)=4.89 μm, $\dot{R}(0) = 49.3$ m/s, $R_{eq} = 3.2\ \mu$m; point **a** corresponds to Fig. 2, **b** to Fig. 3 and **c** to Fig. 4.

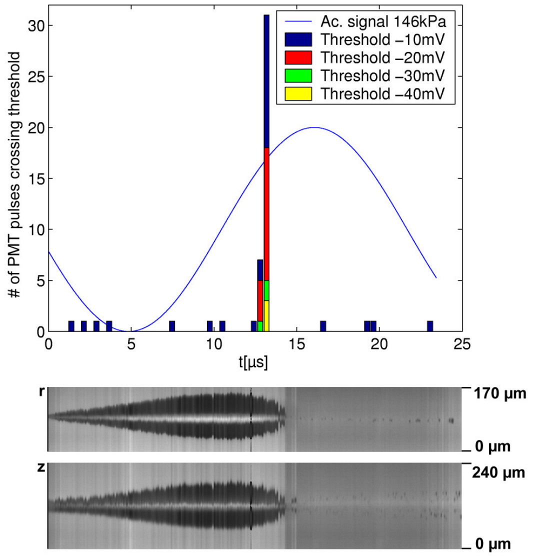

Figure 2: Histogram of 101 shots; streak pictures: phase=3.36, f=44.65 kHz, p_{ac} = 146 kPa, ϵ_1=1.001(4).

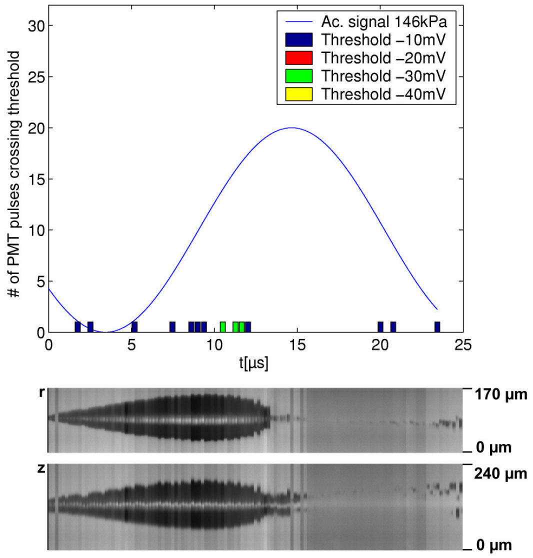

Figure 3: Histogram of 101 shots; streak pictures: phase=3.75, f=44.65 kHz, p_{ac} = 146 kPa, ϵ_1=1.029(3).

This interval was divided into 60 bins of length 0.4 μs. For each bin the number of peaks crossing a certain threshold of PMT voltage was counted for 101 shots and plotted in a bar graph. This graph is compared with streak pictures of the bubble derived from the camera pictures (Figures 2 to 4), where the bubble's extension z is measured along the optical axis, and r perpendicular to it. Unfortunately, the pictures could not be recorded at the same time as the photomultiplier signal, so that the acoustic pressure in the cuvette had slightly changed. This explains the time difference between the main peak and the moment of collapse seen in the streak pictures (e.g., Figure 2). Considering the exemplary results given in Figs. 2 to 4, it can be stated that (i) bubbles generated with fs laser pulses in a sound field emit light when seeded at an appropriate phase, contrary to the case without sound.

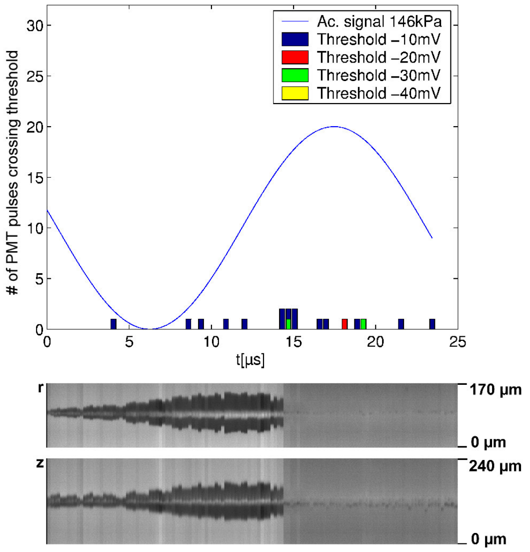

Figure 4: Histogram of 101 shots; streak pictures: phase=2.96, f=44.65 kHz, p_{ac} = 146 kPa, ϵ_1=1.183(24), ϵ_2=0.919(2).

(ii) Strong energy transfer to the bubble by the acoustic pressure is but one factor that determines luminescence strength - equally important is a good sphericity of collapse that is difficult to achieve with the elongated bubbles of our experiment. It appears that the collapsing bubble's excentricity depends on the seeding phase. Defining excentricity ϵ as the ratio of bubble extension in the z- and r-direction of maximum volume, averaged over 5 pictures around this state (corresponding values of ϵ are given in the captions), it is seen that luminescence is only detectable with nearly spherical bubbles (see Fig. 2, $\epsilon \approx 1$). When, in particular, the bubble collapses shortly after laser breakdown and expands widely thereafter, the excentricity before the second collapse is below 1 (see ϵ_2 of Fig. 4) and photon counts are compatible with the thermal noise or scattered light background (or very faint luminescence). The case of Fig. 3 ($\epsilon_1 = 1.029$) also does not show any light emission.

We conclude that light emssion of a bubble generated by a femtosecond laser pulse is possible if the bubble is acoustically driven and seeded at the right phase (see Figure 2). In that case the bubble has a nearly spherical shape in the state of maximum expansion that leeds to a more efficient energy concentration upon collapse, compared with the elongated bubbles.

References

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