Interaction of bubble clouds and solid objects

Topi Tervo, Robert Mettin, Dagmar Krefting, Werner Lauterborn
Drittes Physikalisches Institut, Bürgerstr. 42-44, D-37073 Göttingen, Germany, Email: tervo@physik3.gwdg.de

Abstract

Cleaning and erosion can occur at objects placed into ultrasonic fields in liquids. Here we present high-speed observations of acoustic cavitation bubbles near and on glass plates submerged in the liquid. The dynamics and cleaning activities of bubble structures in the presence of boundaries are investigated.

Setup

An ultrasonic bath (ELAC Nautik L3 Communications, see Fig. 1(a)) with transparent walls, filled with tap water at room temperature, was used at 40kHz and $150-600$W acoustic power. Glass plate samples were placed into the bath in vertical position, perpendicular to the standing wave planes, as shown in Fig. 1(b). The images were made with two high-speed CCD camera systems, namely a HiSIS 2002, with a resolution of 256 x 256 pixels at 1125 fps and up to 16384 frames, zoom objective, and an Imacon 468, with a resolution of 586 x 385 pixels, 8 frames with a maximum of 320000 fps and a Questar QM100 long distance microscope.

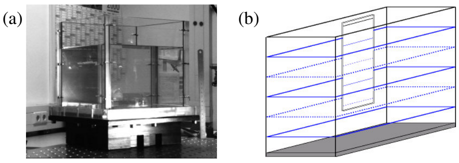

Figure 1: (a) Ultrasonic resonator; (b) Position of a sample in the resonator, dotted lines: nodes of standing wave field, solid lines: antinodes of standing wave field.

Cleaning experiments

In Fig. 2 a view of a cleaning double-layer bubble structure is shown (indicated by the dashed box); bubbles are dark with a brighter background and in the center there is the glass plate in sideview. The left side of the glass has been painted (edding3000 permanent marker). Dark material, not to be confused with bubbles, is emitted on the left side, due to the erosion process by cavitation. The liquid on the right side stays transparent, because there was no ink applied. More detailed results of such cleaning experiments can be found in Krefting et al. [1].

Closeup views of bubble oscillations

Figure 3 shows a closeup view of a bubble cluster on a glass plate surface. Around the glass is a wire which could keep the bubble cluster stationary in the focus position for some time. The eight frames are showing one complete acoustic oscillation period. In the first frame no bubbles can be seen, because they are too small. In frames two to six the bubbles are growing to their maximum radius and then in frames seven and eight they are collapsing. The cluster has an estimated number of bubbles of $N = 300$ and a radius of $A_0 = 0.9$mm. In Fig. 4 another bubble cluster is shown with one frame per period. The even-numbered frames show the bubbles near to their maximum radius and in the odd-numbered frames no bubbles are visible. This picture clearly shows a period-doubled, or subharmonic, oscillation.

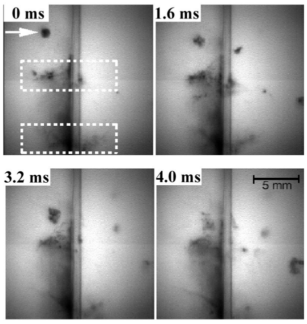

Figure 2: Sideview of a painted glass plate (only left side is painted). A double-layer structure (dashed boxes) is active on the surface. On the left side eroded material is emitted.

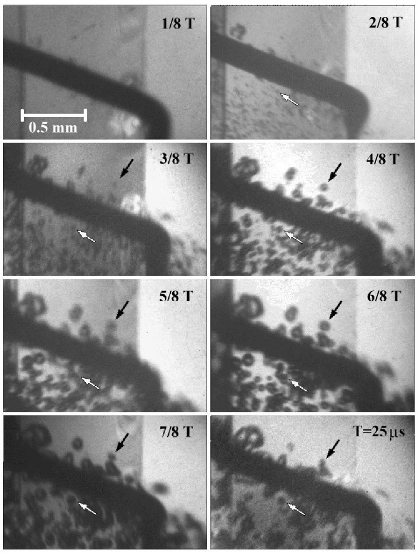

Figure 3: A period of a bubble cluster oscillation is shown. The cluster has formed around a glass plate with a wire.

Model for bubble clusters

To evaluate the bubble dynamics a model for bubble cluster oscillations is used [2], given by Eqs. (1)-(5). This set of differential equations is for a single, monodisperse (all N bubbles have the same radius), spherical cluster in the

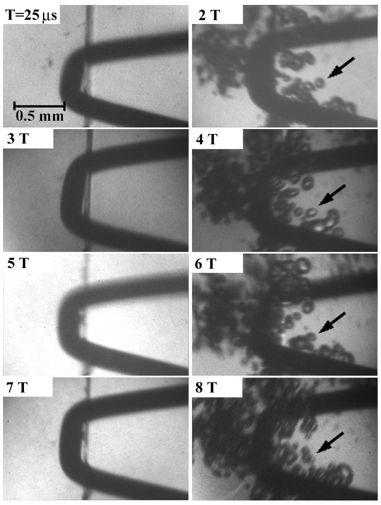

Figure 4: One frame per period of a bubble cluster oscillation is shown. The period has doubled to $2T = 50\mu$s.

free liquid:

$$A\ddot{A} + \frac{3}{2}\dot{A}^2 = \frac{p_c - p_I}{\rho_f} + \frac{R}{\rho_f c}(\dot{p}_c - \dot{p}_I) \qquad (1)$$

$$\left(1 - \frac{R}{r_b}\right) R\ddot{R} + \left(\frac{3}{2} - \frac{2R}{r_b} + \frac{R^4}{2r_b^4}\right)\dot{R} = \frac{p_R - p_c}{\rho_f}, \qquad (2)$$

$$NR^2\dot{R} = A^2\dot{A} \qquad (3)$$

with

$$p_I = p_0 - \hat{p}\sin(\omega t), \quad r_b = \frac{A}{N^{1/3}} \qquad (4)$$

$$p_R = \left(p_0 + \frac{2\sigma}{R_0}\right)\left(\frac{R_0}{R}\right)^{3\kappa} - \frac{2\sigma}{R} - \frac{4\mu}{R}\dot{R}, \qquad (5)$$

Here $A = A(t)$ is the cluster radius and $R = R(t)$ is the bubble radius. p_I, p_c, $\hat{p}$ and p_0 are the driving pressure, the pressure in the cluster, the driving amplitude and the static pressure. c, ρ_f, μ, σ are the sound speed, density, viscosity, surface tension of water and κ the polytropic exponent of air. R_0 is the equilibrium radius of all bubbles. The driving frequency ω is in all calculations $\omega = 2\pi \cdot 40$kHz.

Results

The camera resolution does not allow to identify bubbles smaller than 5μm, so the small oscillations around the equilibrium radius cannot be observed. Also the measured bubble size can only be determined with an error of 5μm. Figure 5 shows measured radii of two bubbles from Fig. 3 (arrows) and fitted parameter calculations from a single bubble model (Keller-Miksis [3]) and from the cluster model. The latter can reproduce the experimental data better, in particular the long phase at large bubble volume. With the cluster model it is also possible to simulate the period doubling from Fig. 4 (see Fig. 6).

Conclusion

The cleaning and erosive activity of bubbles in an ultrasonic bath at 40kHz was investigated (details given in [1]). Only bubbles on or near the surface are involved in the cleaning process. Structure formation is typically observed and becomes important, because of stronger erosive impact. Bubble cluster oscillations, also period doubling, can be modelled by a set of differential equations (see Eqs. (1)-(5)). This model is only valid for a cluster in absence of boundaries, but gives reasonable results in this case with a boundary. The collapse strength of the calculated bubble in the cluster is not as intense as in the single bubble model, but in consideration of the number of bubbles collapsing simultaneously, it can be assumed that these structures have a higher erosive power than single bubbles.

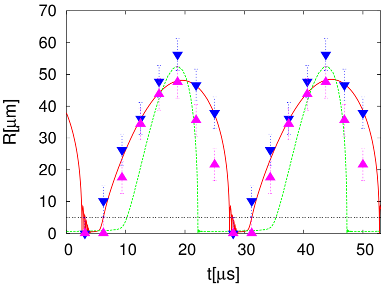

Figure 5: Measured bubble radii from Fig. 3 (arrows), simulated single bubble oscillation (green, dashed line) with $\hat{p} = 2 \cdot 10^5$Pa and $R_0 = 0.8\mu$m, and simulated bubble oscillation (red, solid line) in a cluster with $p_0 = 10^5$Pa, $\hat{p} = 3.7 \cdot 10^5$Pa, $N = 300$, $R_0 = 1\mu$m and $A_0 = 0.9$mm. The line at 5μm indicates the experimental resolution.

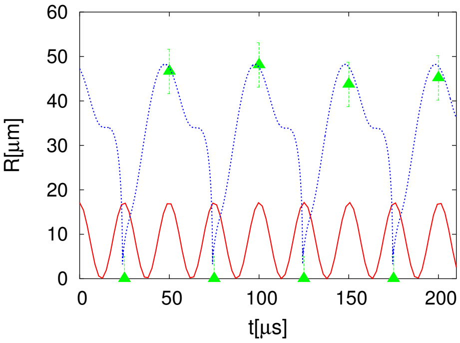

Figure 6: Measured bubble radii from Fig. 4 (arrow), simulated period doubling of bubble oscillation in a cluster (blue, dotted line) with $p_0 = 10^5$Pa, $\hat{p} = 3.7 \cdot 10^5$Pa, $N = 600$, $R_0 = 17\mu$m and $A_0 = 0.8$mm, and the driving pressure (red, solid line).

Acknowledgement

This work was supported by the German Ministry of Education and Research (BMBF project “Untersuchung von Kavitationsfeldern”).

References

[1] D. Krefting, R. Mettin, W. Lauterborn: High-speed observation of acoustic cavitation erosion in multibubble systems. *Ultrasonics Sonochemistry, in press.*

[2] R. Nigmatulin, I. Akhatov, N. Vakhitova, E. Nasibullayeva: Bubble Cluster dynamics. *Nonlinear Acoustics at the turn of the millenium* (1999), 455-458.

[3] J. Keller, M. Miksis: Bubble oscillations of large amplitude. *J. Acoust. Soc. Am.* **68**(2) (1980), 628-633.