EVOLUTION OF ACOUSTIC CAVITATION STRUCTURES NEAR LARGER EMITTING SURFACE

A. Moussatov+, R. Mettin#, C. Granger+, T. Tervo#, B. Dubus+ and W. Lauterborn#
+IEMN département ISEN, UMR CNRS 8520, Lille, France
Drittes Physikalisches Institut, Göttingen University, Germany

Abstract

Cavitation bubble structures generated by a large sonotrode surface are analyzed using high speed cameras. When the acoustic intensity increases, classical dendritic bubble filaments or Acoustic Lichtenberg Figures (ALF) disappear and a conical bubble structure (CBS) is observed. The CBS is constituted by a network of dense bubble clusters connected by thin filaments of fast moving bubbles. The transition from ALF to CBS is explained as a consequence of spatial reduction of phase coherence due to acoustic non linear effects.

Introduction

Cavitation bubbles are known to self-organize as the result of their interaction with the acoustic field (primary Bjerknes force) and of interaction between nearby pulsating bubbles (secondary Bjerknes forces) [1, 2]. Dendritic bubble structures, also denoted Acoustic Lichtenberg Figures (ALF), are observed near pressure antinodes in standing acoustic wave fields. Recently, it has been reported [3] that large horn-type vibrating surfaces (with diameter comparable with the acoustic wavelength) produce a new type of bubble structure at the vicinity of their surface: bubbles gather into streamers which constitute a conical shape. This Cone Bubble Structure (CBS) does not take place in a standing acoustic wave field and remains stable at high acoustic intensities (8 W.cm^{-2}). ALF and CBS observed at the vicinity of a large emitting surface are investigated in this paper by means of high speed cameras.

Experimental set-up

The experimental set-up consists of an axisymmetrical horn-type transducer driven at its resonance frequency (f = 20.5 kHz, T = 48.8 μs) radiating into a large water tank. The sonotrode diameter (120 mm) is approximately equal to 1.64 λ_f (where λ_f is the acoustic wavelength in water). The sonotrode is mounted vertically in order to have the radiating surface a few cm below the water free surface. Images are obtained with a HiSIS 2002 camera at 2250 frames per second. Illumination is provided by CW scattered light or by an LED flash (2 μs) phase synchronized with the driving voltage signal.

Acoustic Lichtenberg Figures

At low acoustic intensity (I < 1.5 W.cm^{-2}), an ALF of conical shape is observed below the sonotrode (Fig. 1). It consists of thin streamers converging toward the symmetry axis. Each streamer is made of small fast moving bubbles.

High speed images

High speed pictures of the conical ALF made with synchronous flashes are displayed in Fig. 2. All individual bubbles vibrate in phase (here close to their maximum radius) and this phase is constant during the acquisition (5000 periods). Individual bubbles move very fast (>1 m.s^{-1}) along streamers while surrounding liquid (colored with ink) stays almost motionless.

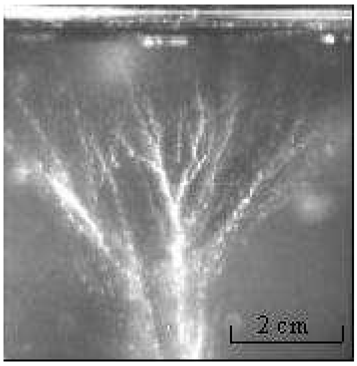

Figure 1: Conical ALF (scattered light).

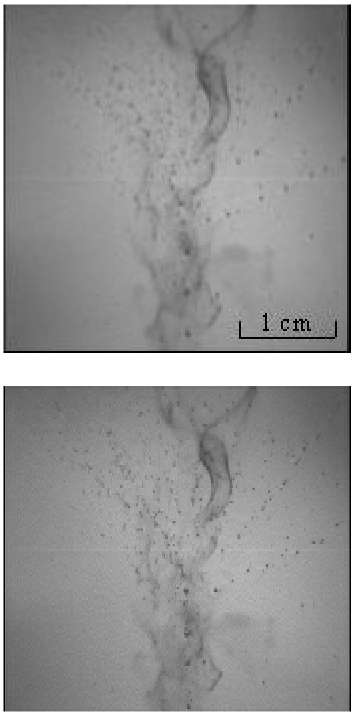

Figure 2: Conical ALF (synchronous background flash). Images are separated by 0.89 ms (18 T).

Analysis

The pressure amplitude distribution at the vicinity of the sonotrode, obtained from linear finite element computation [4], is displayed in Fig. 3. A high pressure zone is found on the symmetry axis, a few cm away from the sonotrode surface. In the experiment, bubble nuclei are located at the sonotrode surface. Acoustic radiation force pushes them away from the sonotrode, and the primary Bjerknes force attracts them to the high pressure zone. Streamer junctions result from attractive secondary Bjerknes forces between individual bubbles.

Cone bubble structure

General description

The CBS starts forming for $I > 1.5$ W.cm^{-2} from bubble nuclei at the sonotrode surface. The bubbles get ejected from the surface and constitute big streamers of dense clusters. Each streamer moves away from the surface toward a fixed point on the symmetry axis. The converging streamers build up a conical shape which is remarkably stable (Fig. 4). When the intensity is increased up to 8 W.cm^{-2}, the number of streamers increases but the shape of the CBS is unchanged. Moreover, the CBS is unaffected by changes of boundary conditions (smaller tank, deeper immersion of the horn, non vertical horn…).

High speed images

The CBS takes place in a complicated wave field. When synchronous flashes are used, bubbles localized in a small zone still vibrate in collective phase but this phase changes on successive frames (Fig. 5). This phenomenon results probably from non linear effects in acoustic wave propagation.

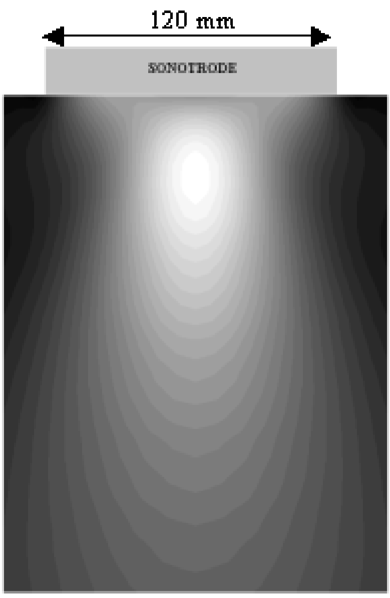

Figure 3: Computed pressure amplitude isocontours (higher pressure is colored brighter).

(a) (b)

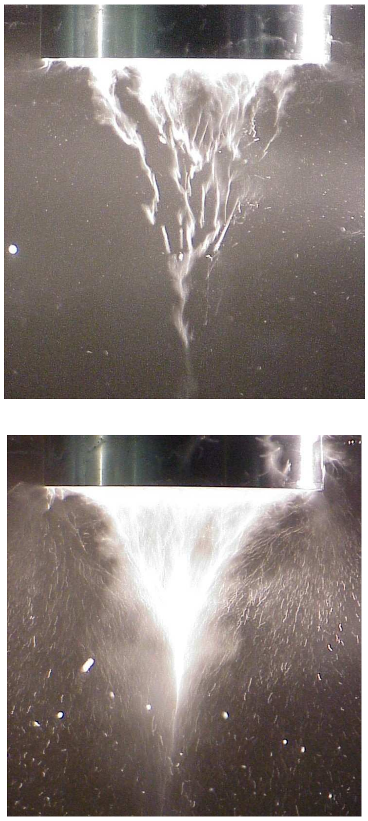

Figure 4: CBS (scattered light), (a) $I = 3.5$ W.cm^{-2}, (b) $I = 8.2$ W.cm^{-2}.

(a) (b)

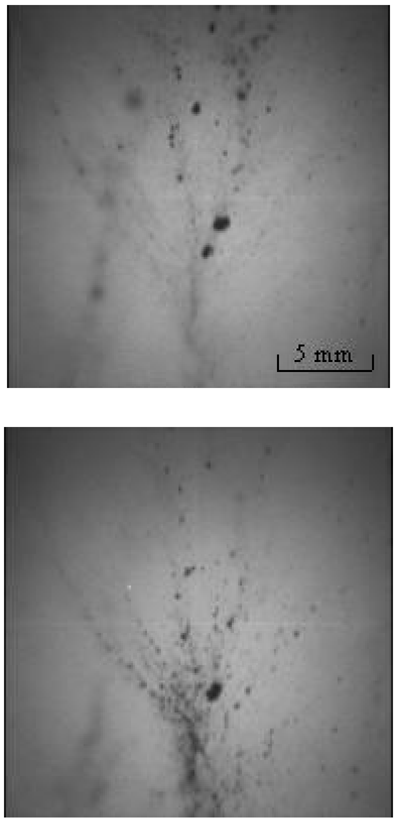

Figure 5: CBS (synchronous flash)
Images are separated by 0.89 ms (18 T)
(a) most bubbles small (near collapse),
(b): most bubbles large (near maximum)

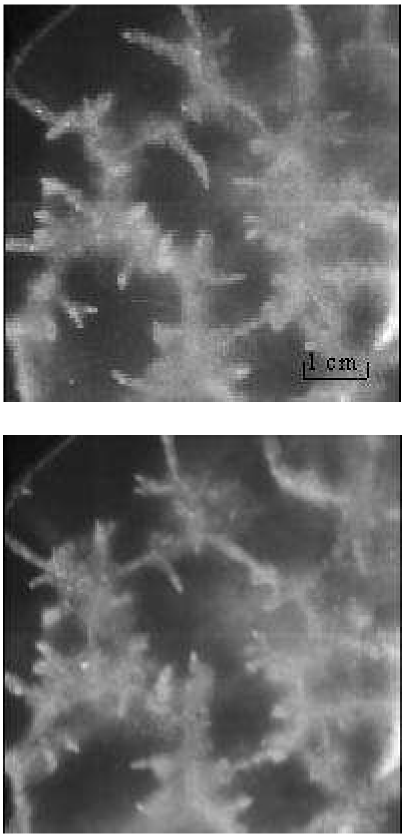

Figure 6: CBS. Sonotrode surface (scattered light). Images are separated by 14.6 ms (300 *T*).

High speed images of the sonotrode surface are displayed in Fig. 6. Starting from bubble nuclei at the surface, thin streamers of bubbles are ejected from the surface and attracted toward fixed positions where large streamers are constituted. The positions of bubble nuclei and thin streamers fluctuate. The position of large streamers remains stable.

When power is turned on, the CBS slowly builds up as displayed in fig. 7. At first, thin bubble streamers similar to those constituting the conical ALF are observed. As power increases, existing thin streamers gather into dense bubble clusters. Only clusters moving away from the surface at medium speed (~20 $cm.s^{-1}$) are still observed. At higher power, the number and size of clusters increase. Thin streamers of bubbles moving at high speed (~80 $cm.s^{-1}$) between the clusters appear leading rapidly to constitution of the CBS.

The CBS is also observed when pulsed excitation is used (Fig. 8). Pulse duration is 300 *T* and pulse rate 2 Hz. During the first pulse, only dense bubble clusters are present. During the second pulse, the conical shape already exists mainly constituted by bubble clusters. During the third pulse, small bubbles move along thin streamers between the clusters.

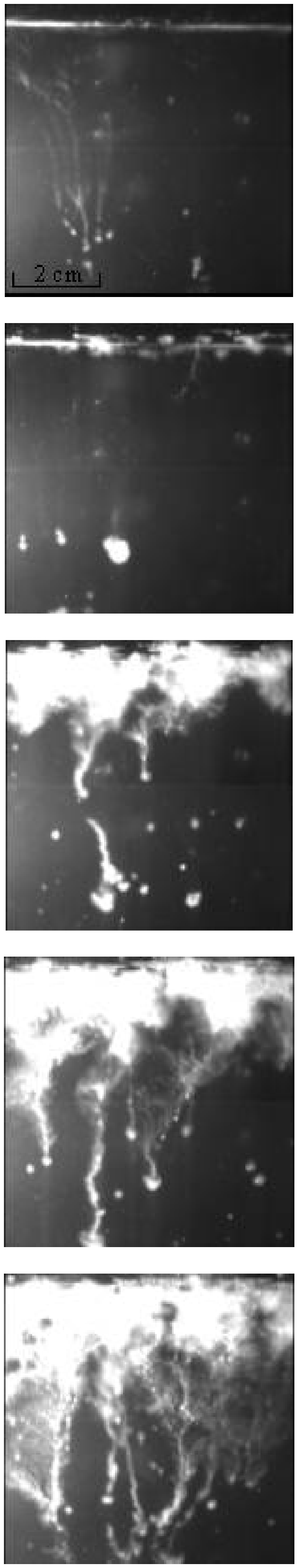

Figure 7: How CBS builds up when power is turned on (scattered light). Time increases from top to bottom. Length of sequence: 1.47 s.

Analysis

A possible mechanism of CBS generation is proposed hereafter. As acoustic intensity is increased, phase coherence is lost on a large spatial scale in the acoustic field because of non linear effects. The ALFs are therefore destroyed. However, phase remains coherent at a smaller scale and very dense bubble clusters are created resulting from large attractive secondary Bjerknes forces between individual bubbles. When interacting with external forces (primary acoustic field or other clusters), a cluster displays a behaviour similar to single bubbles with additional capabilities of modifying its shape and increasing its size (by attracting more bubbles). As bubbles, clusters move away from the surface and toward the symmetry axis under the combined effect of acoustic radiation force and primary Bjerknes force. Nearby clusters also attract each other due to secondary Bjerknes forces. If the acoustic intensity is increased further, attractive force from larger clusters starts to overcome cohesive force of smaller clusters and individual bubbles move from smaller to larger clusters creating small connecting streamers. The final picture of the CBS is therefore made of dense bubble clusters moving toward a fixed point of the symmetry axis and of thin streamers of fast moving bubbles jumping from cluster to cluster.

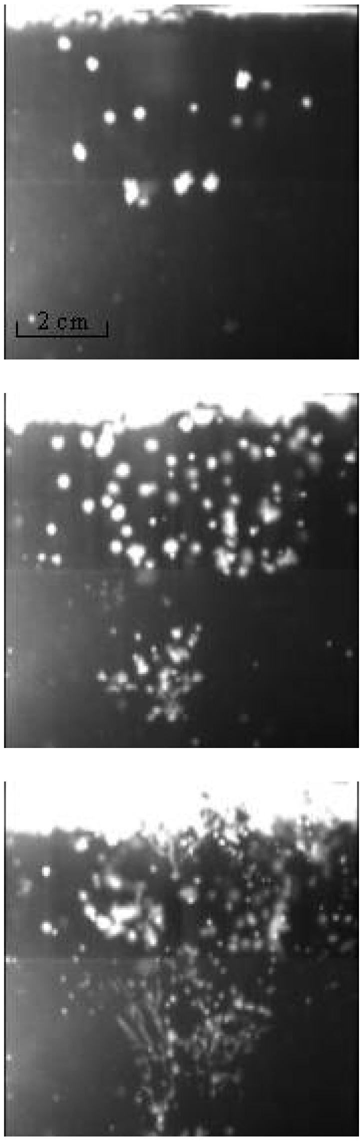

Figure 8: CBS under pulsed excitation. Pulses 1 to 3.

Conclusion

Although ALF and CBS have different microstructures, they are both constituted by thin streamers of fast moving bubbles. The transition from ALF to CBS observed when acoustic intensity is increased could result from the reduction of the spatial coherence of the acoustic phase due to non linear effects in acoustic wave propagation. Experiments with pulsed excitation show that the conical shape of the CBS is determined by acoustical phenomena. However, the exact mechanism leading to this conical shape has still to be identified.

References

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[4] ATILA version 5.2.2, user’s manual, ISEN, Acoustics Laboratory, 2003.

Acknowledgements

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