Introduction

The active agents of many applications of strong ultrasonic fields in liquids are cavitation bubbles [1]. Their violent collapse can cause surface erosion and chemical reactions, both used, for instance, in cleaning and sonochemistry. However, the local distribution of bubbles and therefore their action is usually inhomogeneous – a shortcoming for most purposes. Often bubbles are localized in so-called streamers (see Fig. 1 for an example). On the way towards spatially controlled bubble configurations, the details of bubble creation, motion, and annihilation have to be clarified, which is still a challenging task.

![Fig. 1: Filamentary streamer structure in tap water near a standing wave antinode (frequency: 25 kHz, pressure amplitude: 150 kPa, scale: 4 cm, exposure: 20 ms, scattered light).](image)

To the naked eye, bubble structures from ultrasound in the 20 kHz range often appear as connected filamentary branches [1,2], see Fig. 1. High-speed observations reveal that streamers consist of individual bubbles that usually move rapidly towards a common central cloud or cluster. From short time exposure pictures one can measure [3] bubble sizes (a few
200 µm equilibrium radius) and bubble velocities (10 to 100 cm/s). The clustering emerges near pressure antinodes of the standing sound wave which is mainly due to the primary Bjerknes force [1,2,4]. Neighboring bubbles are attracted by the secondary Bjerknes force [1,2,5] which leads to frequent collisions and coalescence.

**Experimental set-up**

Besides single or double exposure CCD photographs, we employ high-speed CCD cameras (up to 2250 frames per second [6]) with appropriate magnifying optics to record and subsequently identify whole bubble tracks in a streamer, compare Fig. 2. The recording length at maximum recording speed can amount up to 6.4 seconds. A stereoscopic observation is possible to reconstruct the three-dimensional bubble positions. In several steps, the raw image data is processed to enhance contrast, localize bubbles, determine their size and shape, and finally to track them by identifying identical bubbles on subsequent frames [7].

![Fig. 2: Set-up for stereoscopic high-speed recording of bubble motion in a streamer. The lighting can be accomplished by background flashes, as indicated, or continuously to record the light reflected from the bubbles. The angle between the cameras might be changed as well.](image)

**Results**

An example of stereoscopic raw data is given in Fig. 3. A streamer forming a central cluster has been recorded in scattered light at 1120 frames per second, and one double frame from this series is shown. Clearly, individual bubbles can be identified, well separated from each other (different to the long exposure picture Fig. 1). The left and right view pictures look similar, because the camera angle is relatively small in this case.
After image processing and a bubble identification and tracking procedure, individual bubble paths have been extracted from the data. They are plotted in Fig. 4 in different grey shades. The synopsis of all tracks corresponds to a long term exposure and reveals a structure comparable to parts of Fig. 1. The principal motion of all bubbles is towards the center of the cluster. Some bubbles form Y-shaped branches and merge before they reach the center. This phenomenon, due to the secondary Bjerknes force, is typical for increased bubble density and is the reason for the observation of branched filamentary patterns.
The results show once again that acoustic cavitation structures are dynamic objects that are formed by fast moving bubbles. In contrast to a common notion, the origin of the bubbles seems not to be the region of highest pressure amplitude (which would be near the cluster center), but appears to be rather located at low pressure regions and/or the container walls. However, too small bubbles can not be resolved optically and elude an observation.

Simulations

If recorded bubble sizes, positions and velocities are used as initial conditions for the simulation, a comparison of real and calculated bubble tracks can be performed. A first test with two–dimensional data is presented in Fig. 5. The recording (a) shows the pixel positions of bubbles on 20 consecutive frames (the main direction of motion is indicated by the arrows). The simulation (b) produces a qualitatively similar picture by application of a particle model approach [8]. The model calculates the acting forces on each bubble (added mass, primary and secondary Bjerknes, and drag) and iterates the bubble positions in time. The results are qualitatively consistent, while quantitavely still differences appear: the real bubbles run faster than the simulated ones.

![Fig. 5: Comparison of experimentally recorded (a) and simulated (b) bubble tracks in two dimensions (projection). The scale on both pictures is the same. The temporal distance between successive crosses of a track corresponds to 0.44 ms in (a), and to 1 ms in (b) [Picture (a) by Stefan Luther].](image)

Conclusion

We have reported stereoscopic observation of individual bubble motion in acoustic cavitation streamers. By image processing and a tracking procedure, the bubble tracks can be followed in three dimensions. The bubble translations towards a central streamer cluster have been shown as an example, and we expect clarification of the bubble motion in different cavitation structures by this approach in the next time.
The approach to model acoustic cavitation bubbles one-to-one by a particle simulation with real world parameters shows a reasonable agreement with the experiment. It turns out that the simulated bubbles move slower than the observed ones, which might be due to an insufficient drag model. Further investigations of drag and near range interaction of μm-sized strongly oscillating bubbles are required.

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References