Comparison of cavitation bubble arrays at different frequencies

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Abstract

Arrays of bubbles are formed in gassy water in a larger water tank under sonication at different ultrasonic frequencies from around 40 kHz up to 200 kHz. We investigate details of the structures with respect to similarities and frequency scaling. The experimental methods include high-speed imaging and acoustic pressure measurements. Visually the structures appear rather similar at all investigated frequencies: lines of equidistant, equally sized bubbles appear close to pressure nodal zones. Also, the relations of array bubble size to linear resonance bubble size and of interbubble distance to acoustic wavelength are roughly similar, which suggests a universal scaling with inverse frequency.

Introduction

Acoustic cavitation is a well known phenomenon with a variety of applications [1, 2, 3]. Although a lot is known about individual bubble dynamics in the linear and nonlinear regimes, multibubble phenomena and bubble interactions are still not completely understood. As applications and basic cavitation research extend the parameter regime more and more, investigations on similarity and scaling of acoustic cavitation are demanded. While some work on specific bubble structures of strongly driven bubbles has already been presented by the authors [4, 5], here we show investigations on weakly driven, larger "degassing" bubbles in a standing wave. A peculiar pattern of such bubbles located in line "arrays" can be found over a broad frequency range from kHz to MHz. Our group has observed similar bubble structures at 230 kHz before [6], but one of the first reports on such arrays has been given by D. L. Miller for a MHz field [7, 8], For this reason, we want to call the phenomenon "Miller arrays". In Miller's original work, also planar arrays of equally sized bubbles are documented, which are not observed here.

Experimental setup

All measurements were performed in a rectangular, water filled glass tank with a sandwich transducer glued to the center of the bottom (see Fig. 1). The tank size was 20 cm x 30 cm x 15 cm (height) with a water level of 13 cm. The diameter of the circular transducer was 5 cm, and it could be driven within a broad frequency range. The water was token from the tap and was always aerated before the measurements. This resulted in oversaturation with air, and a huge number of microbubbles has been present before sonication started.

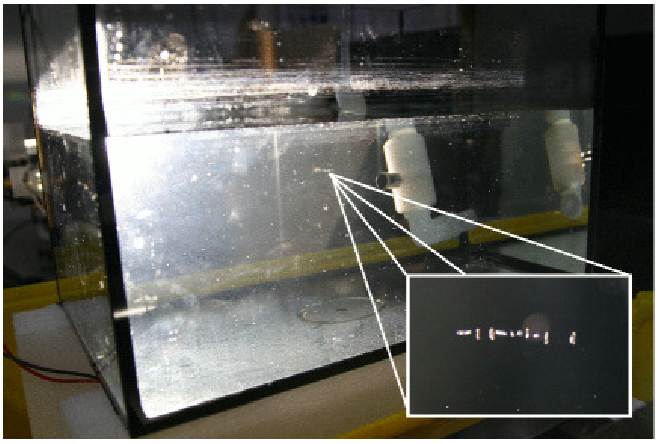

Figure 1: Picture of the test setup showing the glass tank with the transducer glued to the bottom. The applied frequency is 37.65 kHz at the moment. The small picture is an enlargement of the line structure in the center, taken in a long exposure in scattered light: Some of the bubbles are calm and some circle around their rest position. This can be seen by the vertically elongated shapes, which are due to the bubble motion.

Bubble arrays

Under the indicated circumstances, similar bubble structures appear for many different frequencies at small to moderate driving pressures. Close to pressure nodal regions, bubbles of similar size arrange on a sometimes curved line with a characteristic, surprisingly stable distance to each other. From time to time the bubbles start to circle around this line, but only very weak or no volume oscillations of the bubbles have been detected. In many cases, all bubbles of the array move slowly in direction along the line, but keep their interbubble distance (the whole array is shifted). Only if a bigger bubble appears, the smaller ones might be drawn to it and merge. In this way a whole bubble line can coalesce to one bubble, which might then be big enough to raise to the water surface by buoyancy. Figure 2 shows individual frames of high speed recordings of the structures at different frequencies.

The occasional rotational motion of the bubbles around the line axis is most of the time correlated. In a pure side view, it appears as up and down translation due to the 2d projection. From such recordings, it was resolved that direct neighbours move antiparallel and every second neighbour moves in parallel, i.e. if the bubbles would

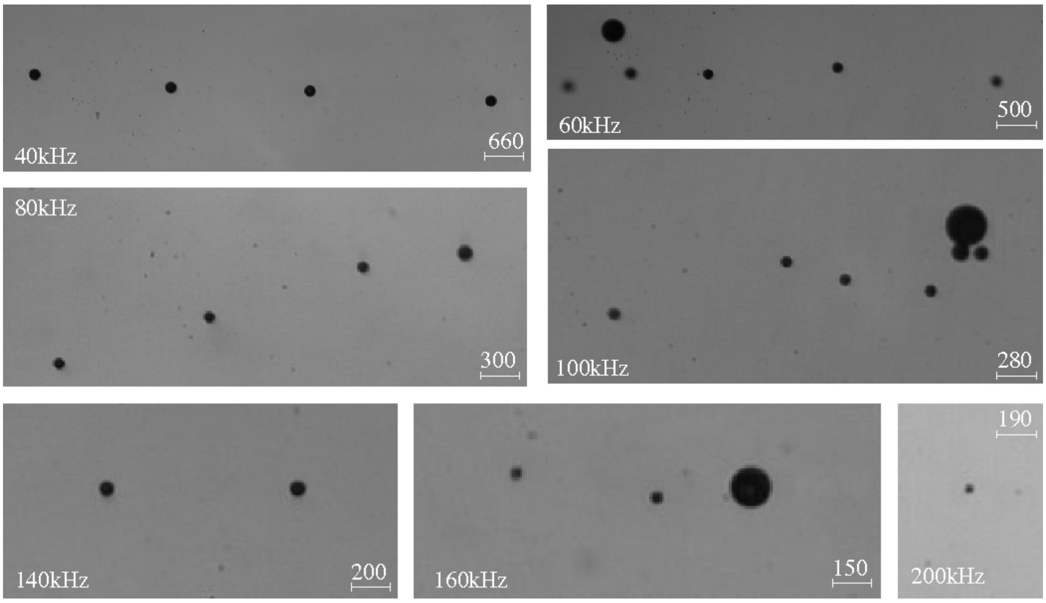

Figure 2: Frames of movies (camera Photron APX-RS, exposure 1 μs) of the bubble arrays at different frequencies from 40 kHz up to 200 kHz, as indicated. The scaling bar in all frames is given in μm. A similarity of the bubble arrays is obvious.

be numbered, all even bubbles move up when the odd ones move down. Slightly inclined observations, as well as with the naked eyes, reveal an ellipse or circle track of each bubble in a plane perpendicular to the array axis. Combined with the antiparallel ups and downs in the side projection, it can be concluded that the bubbles rotate in the same orientation and with the same angular frequency, but in antiphase to the direct neighbours. Typical revolution periods are of the order of 100 acoustic cycles in the 40 kHz case, but have not been evaluated rigorously yet.

The coherent bubble motion is destroyed if visible surface deformations or surface oscillations of the array bubbles appear. Then, the motion perpendicular to the array axis starts to be more erratic, and also the radius of the excursions from the axis can increase. Interestingly, neighbouring bubbles can be "infected" by surface instabilities: After one bubble started with surface oscillations, the next ones have been observed to start some time later, too, and this neighbour triggering might proceed along the whole line.

If the acoustic pressure amplitude in the tank is increased sufficiently, streamers of smaller bubbles appear in the planes between the array lines. These streamers then are going to feed the array bubbles with additional gas, which leads to bubble growth and finally the disappearence of the structure.

Pressure measurements

The pressure field in the tank was partially mapped with a hydrophone (Brüel & Kjaer 8103) in planes parallel to the transducer, and in the vertical direction. An example is given for the 100 kHz case in Fig. 3. It is seen that a standing wave pattern with imperfect nodes and a certain near field structure close to the transducer emerges. The location of the bubble arrays within the wave field could not be determined exactly yet, but they appear close to measured pressure minima, which is consistent to the observation of only weak bubble pulsations.

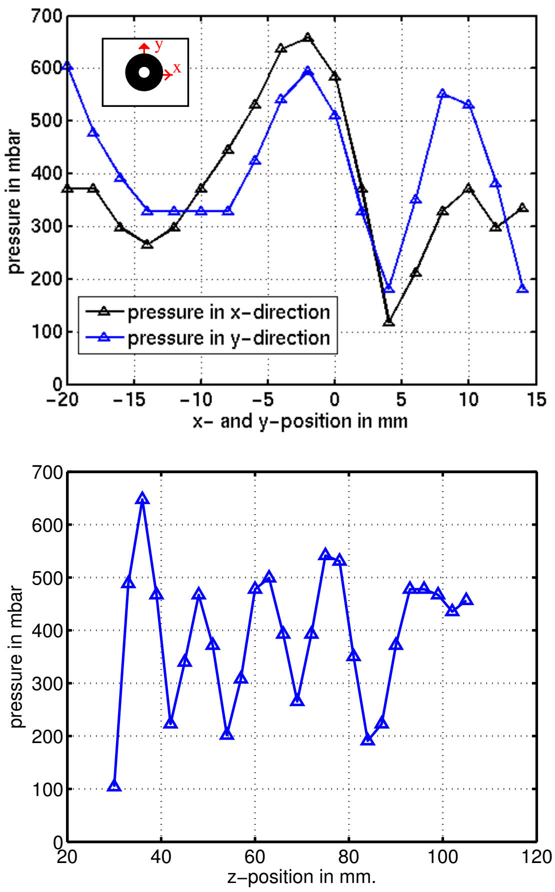

Figure 3: Acoustic pressure amplitude measured at 100 kHz; top: at a distance of 3.65 cm above the transducer (x- and y-axis are parallel to the walls of the tank, orientation shown schematically in the inset); bottom: vertical distribution above transducer center (z-axis).

Scaling measurements

Bubble sizes and distances in the arrays have been determined from high-speed recordings for the examples presented in Fig. 2. A comparison of the reciprocal of typical bubble radii in the Miller arrays, R_{Miller}, at the different frequencies is given in Fig. 4 (top). For reference, the reciprocal linear resonance (Minnaert) radius [2] is indicated as well. It is seen that the observed bubbles are slightly larger than resonance size. From Fig. 4 (bottom) it can be observed that the normalised array radii, i.e. the relation R_{Miller}/R_{res}, yields an almost constant value of about 1.25.

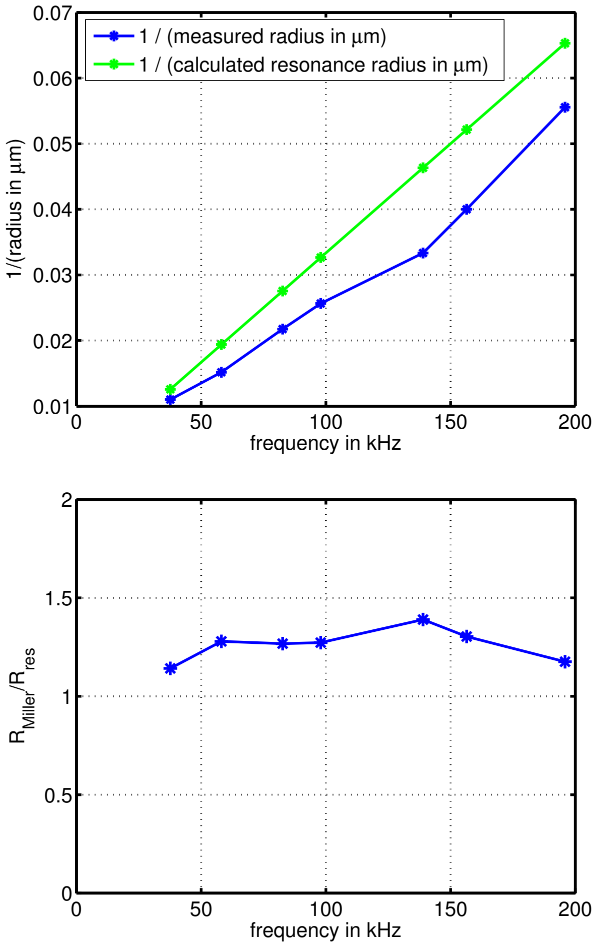

Figure 4: Top: reciprocal of the measured radii from the recordings vs. frequency, and of the reciprocal linear resonance (Minnaert) radius vs. frequency. Bottom: normalised array bubble radii R_{Miller}/R_{res} vs. frequency.

Measurements of typical interbubble spacings are given in Fig. 5 (top), plottet as reciprocal distances vs. frequency. As a reference, the acoustic wavelength λ is also given reciprocally. Again, the normalised quantity, i.e. the typical bubble distance divided by the wavelength, is nearly constant over the investigated frequency range, as can be seen in Fig. 5 (bottom). Its value falls roughly into an interval between 1/15 and 1/20, with a mean of 0.057.

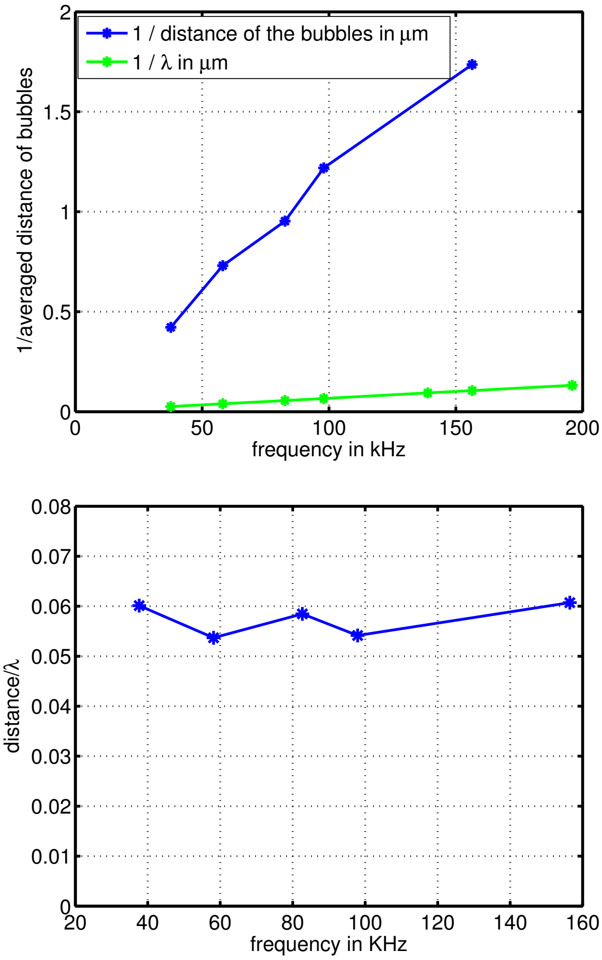

Figure 5: Top: reciprocal of the typical (averaged) distance of the bubbles in the arrays vs. frequency, and inverse acoustic wavelength $1/\lambda$ vs. frequency. Bottom: distances normalised by wavelength vs. frequency (note that the value at 200 kHz has not yet been measured).

Conclusion

For a broader frequency range, it is possible to observe "Miller arrays" of bubbles in standing ultrasound waves and sufficiently gassy water. Characteristics of this cavitation (or rather "ultrasonic degassing") structure are bubbles slightly larger than resonance size that arrange in a line with equidistant spacing. A common feature is the circling of some or all bubbles in the array perpendicular to the common axis. From sound pressure measurements and from the absence of stronger volume oscillations of the bubbles, it is concluded that the array location is close to pressure nodal zones, as in the original results by Miller [7, 8]. Additionally, we find a reasonably good scaling of structure properties with acoustic wavelength (or 1/frequency), in particular bubble sizes and distances, in the range between 40 kHz and 200 kHz. Preliminary results indicate that the scaling might roughly be valid up to 1 MHz, but further investigations are needed.

In spite of the good observability and reproducability of this generic bubble structure, its creation mechanism is still unknown. While the origin of the array bubbles is clearly an ultrasonically maintained degassing process, it is unclear what limits their sizes and prevents a coalescence due to (standard) secondary Bjerknes forces [2]. A good candidate are “higher order” secondary Bjerknes forces caused by monopole-dipole and dipole-dipole interaction of neighboring bubbles [9]. This concept has some experimental evidence, as a high-speed jitter of the bubbles synchronously with the sound field has been recently resolved optically [10]. The jitter is probably due to the acoustic velocity field and additional forces caued by the fininte bubble size, and its quantitative effect on adjacent bubbles will be evaluated elsewhere. The circling of the bubbles might be included into this formalism, and it might result from a positional instability on the axis center. A further complication arises, of course, if surface oscillations of the array bubbles are present, which apparently leads to an additional, more chaotic component of bubble interaction.

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