Research Notes

High-speed photography of transient excitation

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Transient excitation can cause the unstable growth and collapse of bubble nuclei, as well as enhancing the stable cavitation of larger bubbles. These unstable collapses have been photographed at 8000 f.p.s., the resulting pictures agreeing well with predicted numerical solutions. These cavities, unlike those normally studied with high-speed photography, are generated by purely acoustic methods, and so the events are as would occur during *in situ* acoustic cavitation.

Keywords: cavitation; bubbles; bioeffects; sonoluminescence

When a liquid is insonated with a high intensity sound field, it may cavitate in a number of different ways. In a continuous-wave sound field, the cavitation may be stable or unstable (also known as transient). If a pulsed sound field is employed (or at the start of continuous-wave insonation), the volume pulsations induced in bubbles within the liquid differ from their steady-state motions. This has an effect on the stable oscillations of bubbles of just below resonance size. At both kilo and megahertz frequencies, transients in the radius/time function cause the minimum bubble volume reached during the early oscillatory cycles to be less than that expected from the steady-state motion. The internal bubble temperature and pressure are thus higher, increasing the number of free radicals created by these conditions. Thus the luminescence resulting from the radiative recombination of these radicals is enhanced above that expected during the steady-state. From numerical solutions of the Rayleigh–Plesset equation, this 'transient excitation' of bubbles has been shown to occur at the start of insonation, and the resulting enhancement of sonoluminescence was detected by photomultiplication[1].

In addition to predicting these enhanced stable oscillations of bubbles of just less than resonance size, the numerical solutions also predict that at 10 kHz, transient excitation causes the growth of micron-sized cavities (which are originally much less than resonance size). These reach a maximum radius of 0.35 ± 0.10 mm, before collapsing unstably[1]. The growth and collapse takes of the order of an oscillatory cycle. It was shown that these collapses too may produce sonoluminescence[1]. This type of collapse is normally termed 'transient cavitation'; in this Paper it is referred to as 'unstable cavitation', to avoid confusion with the short-lived transients in the radial function which distinguish it from the steady-state oscillation.

In this study, high-speed photographs are taken of the behaviour of bubbles in aerated water at the start of 10 kHz insonation. The pictures show the unstable growth and collapse of initially very small cavities. In addition, stably-oscillating cavities are detected.

Material and methods

Aerated water, at room temperature and under one atmosphere of pressure, was placed in a cylindrical cell to be insonated. The cell was made from two hollow piezoceramic cylinders each 3.1 cm high, between which was sandwiched a 2.9 cm high cylindrical glass segment (*Figure 1*). Each cylinder has a height of 9.3 cm, and inner and outer diameters of 6.9 cm and 8.3 cm respectively. Electrical contact was made through copper strips soldered directly onto the piezoceramic. The outer ceramic surfaces were connected in parallel, as were the inner surfaces. This inner surface, and the water contained, were earthed for two reasons: firstly, to ensure standardized cavitation conditions (since Chang and Berg[2,3] and Apfel[4] have shown that electric fields can affect cavitational processes), and secondly to reduce any pick-up by the hydrophone (Bruel and Kjaer, type 8103) used to measure the acoustic pressure at the axial focus of the cylinder.

The piezoceramic cylinder was mainly capacitative in nature, of value 0.025 μF. Since standard amplifiers operate most efficiently into a real impedance, it was necessary to incorporate it into an L-C resonant circuit to dissipate high power in the cylinder. Therefore the cylinder was placed in series with a tunable solenoid. The sound field generated on axis had an amplitude of 2.4 atm., and a frequency of 10 kHz (though, as the hydrophone traces[1] for this system show, the sound field may take 4 or 5 cycles to build up to its full amplitude).

The system was viewed from above, the vertical optic axis being coincident with the axial pressure antinode. High-speed photographic pictures were taken using a Hadland Hyspeed camera. This has a maximum framing

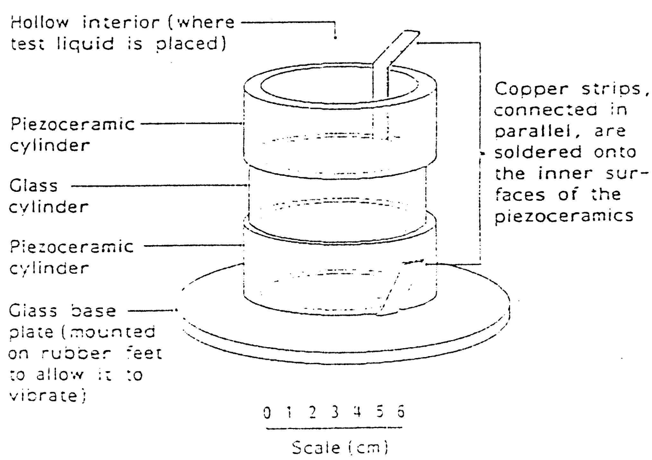

Figure 1 Piezoceramic cylinder used to generate the sound field

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by the introduction of a heated wire[15]. Most of these techniques are discussed in a review by Trevena[16], who emphasizes the distinction between these 'ready-made' bubbles and 'true' cavitation bubbles (which must be generated by tension in the liquid).

The need to place the event at the optical focus can be circumvented by using holographic techniques, which simultaneously image the entire body of the liquid within the field of view (for example, to obtain cavitation nuclei size spectra[17]). In particular, a high-speed holographic camera (operating at up to 300 000 f.p.s.) has been developed[18] which has been used to study the transient responses of bubbles[18,19]. However these authors were not studying unstable cavitation seeded from microscopic nuclei in response to an acoustic field, as has been done in this study. Instead they generated bubbles by electrolysis or by employing a focused laser beam and studied the transients present in their stable oscillations (for example, by imaging the shape oscillations). The kind of transient response studied in this paper, where a seed nucleus grows to about five hundred times its equilibrium radius and then collapses unstably within one acoustic cycle, has not been imaged previously.

Results

The growth of bubbles of much less than resonance size in a 10 kHz field, followed by their unstable collapse in less than an acoustic cycle later under the action of transient excitation, has been photographed using the experimental arrangement described above. The framing rate was 8000 f.p.s., and the depth of focus was 1 mm. *Figures 2* and *3* show two sections of film, each eight frames long. In *Figure 2*, insonation begins between frames 1 and 2. Two bubbles of just less than resonance size (labelled A and B) can be seen quiescent in frame 1. Their radii, as estimated from the film, are 0.10 ± 0.05 mm. They begin to oscillate in frame 2. In frame 4, further bubbles appear and grow to a size of about 0.15 ± 0.05 mm. These bubbles were previously too small to be seen, implying that their equilibrium size must be less than about 0.05 mm. These bubbles have collapsed unstably and have all gone by frame 6.

Bubbles A and B are seen to undergo stable cavitation, as predicted by the computer plots[1]. They do not appear to move out of the depth of focus. They are driven together by the mutual or secondary Bjerknes force[20] (which is attractive between two bubbles both of which are less than resonance size, as in this case), and coalesce in frame 4 to form a single bubble with violent surface oscillations (labelled C). In fact, in frame 5 it almost breaks up again. A third bubble (labelled D), also oscillating stably, travels into the depth of field in frame 3. It continues travelling perpendicularly to the picture, and by frame 8 is leaving the optical focus. Since the inter-frame time is longer than the acoustic period, the stably oscillating bubbles (A, B, C and D) undergo considerable volume change during each frame. Examination of the images suggests that the maximum size reached per pulsation is of the order of 0.6 mm radius.

Figure 3 demonstrates a similar effect, with the bubbles of much less than resonant size growing in frame 3. These then collapse unstably and are all gone by frame 5. A quiescent bubble of near-resonant size (labelled A) is just visible in frame 1. It oscillates stably; a second stably-oscillating bubble (B) enters the field of view in frame 4. The bubble dimensions are similar to those in *Figure 2*.

Discussion

Figures 2 and *3* verify the predictions of the earlier numerical solutions[1]. Bubbles of just less than resonance size (which is of radius 0.3 mm in a 10 kHz sound field[21]) are seen to undergo stable cavitation. Much smaller bubbles grow and collapse unstably (providing photographs of bubble growth from naturally occurring seed nuclei). In particular, these photographs substantiate earlier spatial and temporal predictions about such collapses.

The observation has been made earlier[1] that the maximum size reached during unstable collapses is independent of the initial size of the nucleus (predicted theoretically by Apfel[22]). This is fortunate, since the precise initial size of the bubble nuclei whose growth is photographed in *Figures 2* and *3* cannot be determined. The bubbles undergoing unstable cavitation in the photographs do indeed reach a similar maximum size (when one considers that their initial sizes may vary by several magnitudes). The actual size, as measured on *Figures 2* and *3*, is 0.15 ± 0.05 mm. *Figures 4a* and *b* show the computed radius/time plots (produced as outlined in Leighton[1]) for the unstable cavitation of bubble nuclei,

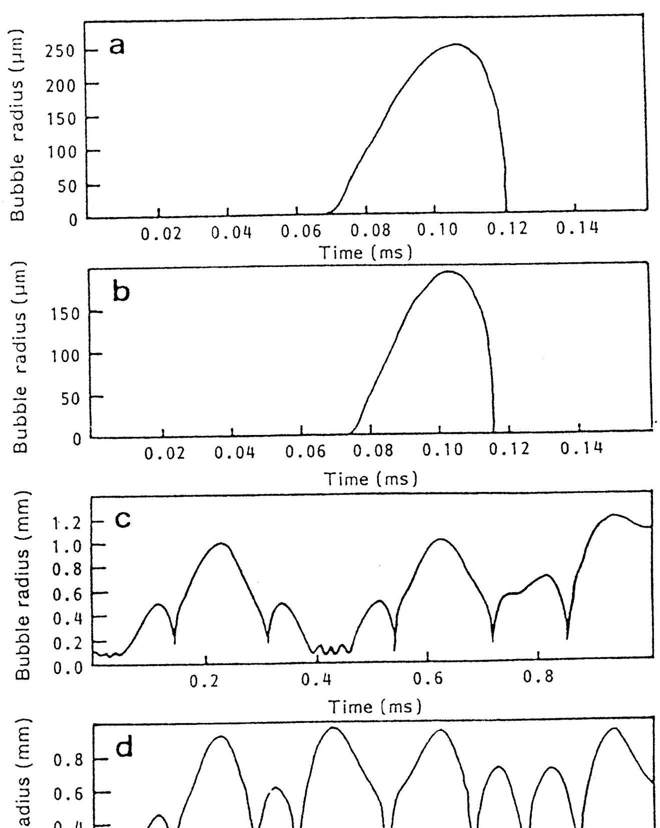

Figure 4 The computed radius/time plots for air bubbles in water under one atmosphere hydrostatic pressure, insonated at 10 kHz with a pressure amplitude of 2.4 atm. (2.4×10^5 Pa). Insonation begins at time $t = 0$, at which point the bubble is stationary and has a radius of (a) 0.5 μm, (b) 0.45 μm, (c) 0.112 mm, (d) 0.10 mm

rate of about 8000 f.p.s. for full-frame photography, taking about 1 s of film in real time. The photographs were taken in the following manner. The camera was started and after it had reached full speed the sound field was triggered. This 10 kHz acoustic signal was pulsed, having a duty cycle of 1:1 (both pulse length and off-time had durations of 32 acoustic cycles). Approximately 20000 frames were taken in a continuous run.

The photographic data presented (*Figures 2* and *3*) show examples of the bubble activity that occurred at the beginning of each of the 10 pulses photographed by the camera at full speed. Since the acoustic frequency was 10 kHz, to satisfy the Nyquist criterion the sampling rate would have to be at least 20 kHz to avoid the possibility of misleading frequency information being present in a given sample. The maximum framing rate of the Hadland Hyspeed is 8000 f.p.s., so therefore care is required when interpreting the results. Firstly, the possibility exists that what appears to be a transient event in an isolated eight-frame sample may in fact be periodic; however, since the transient event did not appear anywhere except near the start of each and every pulse throughout the film, we can be sure that it is transitory in nature. Secondly, the size of the bubble during a complete

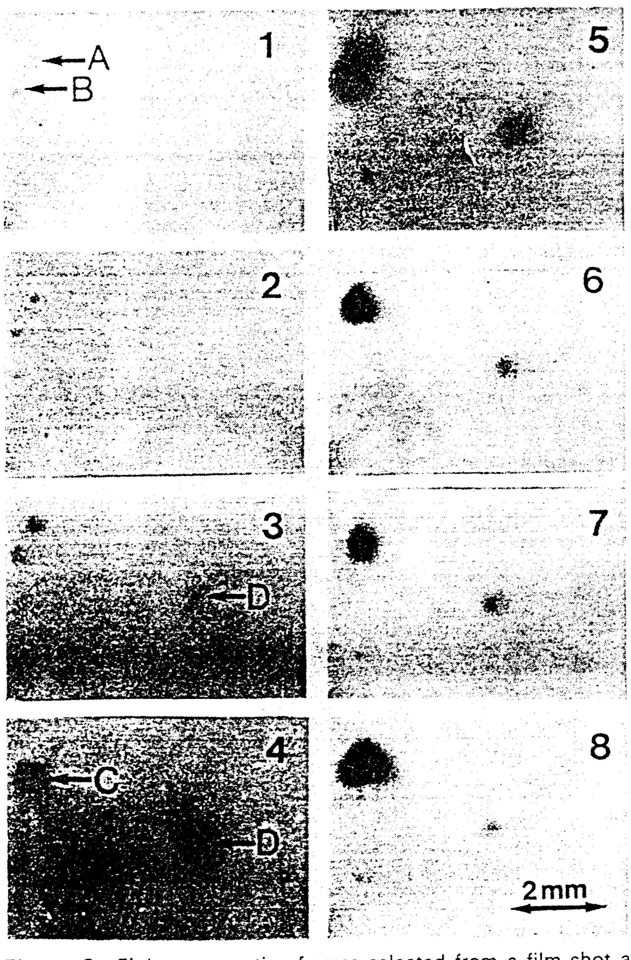

Figure 2 Eight consecutive frames selected from a film shot at 8000 f.p.s., showing the unstable growth and collapse of bubbles of much less than resonance size. Insonation begins between frames 1 and 2. The bubbles labelled A, B and D are of roughly resonance size. In frame 4, A and B (driven together by the mutual or secondary Bjerknes force) coalesce to form bubble C. Bubbles A, B, C and D all oscillate stably. Bubbles that were initially too small to be visible (and so were very much less than resonance size) grow suddenly in frame 4. Most have collapsed unstably by frame 5

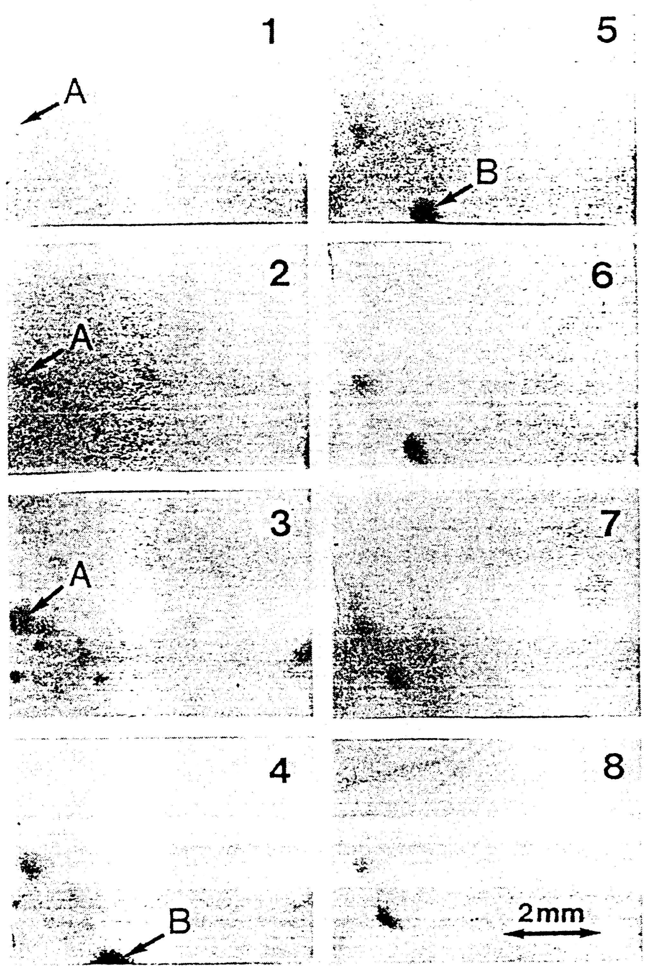

Figure 3 Eight consecutive frames selected from a film shot at 8000 f.p.s. showing the unstable growth and collapse of bubbles of much less than resonance size. Insonation begins between frames 1 and 2. The bubble labelled A is of roughly resonance size. The unstable growth of bubbles which were much smaller than resonance is seen in frame 3; these bubbles have almost all collapsed by frame 6. A second bubble of near-resonance size (B) enters the field of view in frame 4. Both it and bubble A undergo stable cavitation

oscillatory cycle cannot be determined. However, the maximum size reached during the 1/20000 s exposure can be measured from each frame, and can be used to deduce the maximum bubble radius reached, and the associated uncertainty, within an oscillation.

Initially, side-lighting was tried, since stills photography showed it to provide the greatest contrast for bubbles. However, reflections from ripples on the liquid surface tended to mask the bubble activity. Cylindrical screens stopped this, but when higher mangifications were attempted it was found that side-lighting was too weak. For greater illumination, the cylinder was lit from below by standing it on a lamp (an 800 W 'red-head' halogen photo-lamp), so that the bubbles appeared as shadows.

Previous high-speed photographic studies of cavitation have not investigated the acoustically-induced growth of bubbles from these naturally occurring seed nuclei, but have instead relied upon non-acoustic techniques to place a bubble at the optical focus. This can either be done by the introduction of a pre-formed bubble (trapped between glass plates[5], set in gelatin[6], attached to a thin wire[7,8] or adhering to a solid boundary[5,9–11]); or by generating a bubble using sparks[12], focused lasers[13], electrolysis[14], or first insonated at time $t = 0$, of initial radii 0.50 μm and 0.45 μm respectively. The size reached by the bubbles in *Figures 3* and *4* agrees well with these computed radii, though of course the initial size of the nuclei is unknown (it appears to be the trend that as the size of the initial nucleus is decreased, the maximum size reached is reduced, though to a lesser extent). It would be difficult to obtain an exact correlation since, as mentioned earlier, in the first few cycles the sound field has not built up to its full amplitude.

These solutions predict that each growth and collapse will take about 50 μs for the smallest bubbles, and three or four times this for larger bubbles. In *Figures 2* and *3*, the unstable events last, in most cases, for about a frame or so. Since the inter-frame time is 0.125 ms, it is clear that the plots and the photographs agree once again.

The stable cavities, which initially have an equilibrium radius of 0.10 ± 0.05 mm as measured in *Figures 2* and *3*, reach a maximum radius of up to about 0.6 mm. *Figures 4c* and *4d* show the computed radius/time plots of bubbles of initial radii of 0.112 mm and 0.100 mm respectively. These predict similar bubble sizes reached during the stable cavitation, though again an exact correlation is not possible since the initial bubble radii can only be estimated from the film, and (as can be seen by comparing *Figures 4c* and *4d*) the phenomenon is highly non-linear and very sensitive to the initial bubble size.

Conclusions

High-speed photography has recorded the effect of transient excitation on bubbles of much less than resonance size at the start of 10 kHz insonation. The unstable cavitation predicted by the numerical solutions is seen to occur, with both the maximum size attained and the timescales involved of order with the computer plots. In contrast bubbles of just less than resonance size do not behave in the same manner; they undergo stable cavitation (as predicted by the numerical solutions).

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