Bubble - Shock wave interaction

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Introduction

The investigation of shock wave bubble interaction has a long history. For instance, the effect of shock waves from laser breakdown on nearby bubbles has been studied in [1,2] with the bubble motion indicating the shock strength. The interaction of shock waves with bubbles is also important in applications like shock wave lithotripsy and possibly for drug delivery or gene transfer by low amplitude shocks [3]. Impinging of a shock wave on a single cavitation bubble can amplify the collapse shock pressure as well as induce a liquid jet [4,5,6]. The bubble collapses to a disk-like shape perpendicular to the direction of the shock and the jet develops in the direction of shock wave propagation [4]. The maximum amplification of the pressure and maximum reduction in collapse time happens in the case when the shock impinges on the bubble when it collapses [4].

In this work shadowgraph images and pressure profiles of lithotripter shock waves propagating in water are shown, illustrating the characteristics of a typical applied shock wave. The interaction between the shock wave and a laser generated single cavitation bubble in its collapse phase is investigated.

Experimental set up

Figure 1 shows a schematic diagram of the experimental set-up. The expanded beam from a Q-switched Nd:YAG laser (λ=1064 nm, pulse duration 8 ns) (1) is focused by an aberration minimized lens system (2,3) at the centre of a cuvette (19.6 cm × 19.6 cm × 12 cm) filled with distilled water (4). A combination of a high-power flash lamp (5) and a long distance microscope (K2, Infinity) with a very-high speed camera (IMACON 468, DRS Hadland) (6) is used for capturing the fast dynamics of the shock-bubble interaction. A piezoelectric shock wave generator (Piezoson 100, Richard Wolf Germany) (7) is used to focus the shock waves at the centre of the container where the laser focus is located. Pressure measurements are performed by means of a fibre-optic hydrophone (FOPH300) (8). Two delay generators (Stanford DG 535) are used to synchronise laser, flash lamp, camera and the shock wave generator.

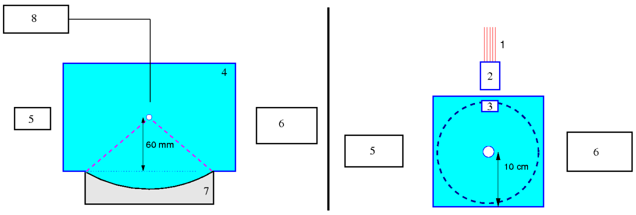

Figure 1: Experimental set up for shock wave - bubble interaction. Side view (left), top view (right).

Shock wave characterization

Propagation

Figure 2 shows shadowgraph images of the shock front near its focus with an interframe time of 1 µs. The exposure time is 10 ns. The position of the focus is visible in the second frame. The shock front diameter at this point is about 1 mm.

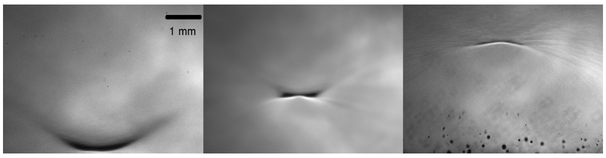

Figure 2: Shadowgraph images of shock wave propagation with interframe time of 1 µs.

Due to the tension tail of the pressure profile (see Figure 4) , some bubbles are produced which can be seen at the bottom of the third image in Figure 2. These bubbles are better visible in Figure 3 that shows a cavitation bubble cloud in which the collapse of the bubbles produces multiple secondary shocks.

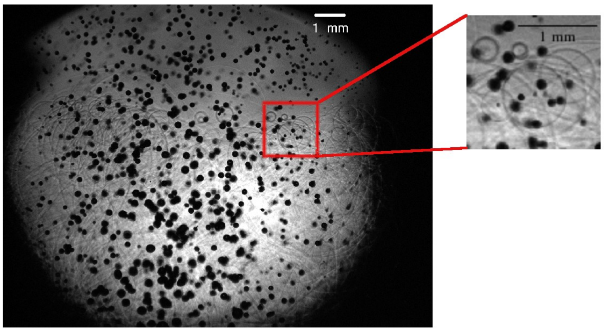

Figure 3: Cloud of cavitation bubbles which are generated due to the tension phase of the applied shock wave.

Shock pressure measurement

The pressure is measured at a distance of 2.56 mm above the focus. Calibration is done considering the variation of the refractive index of water, change of the refractive index of glass itself, water temperature and nonlinearity.

The averaged signal is deconvoluted with the impulse response function of the FOPH. The result is shown in Figure 4, the zero of time corresponds to the maximum of the compression phase (about 78 MPa). The minimum pressure (in the rarefaction phase) occurs about 2.1 µs after the maximum. At this time the pressure drops to about -12 MPa which can rupture the liquid and produce secondary cavitation.

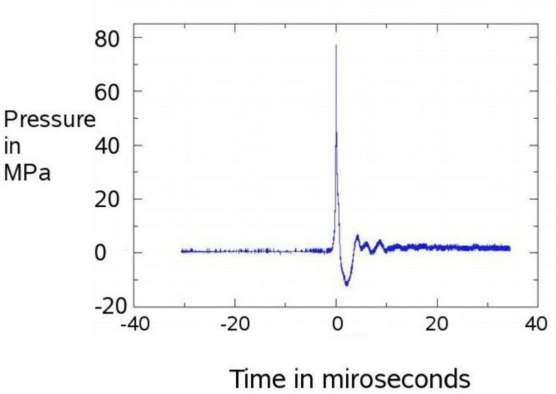

Figure 4: Typical pressure profile of the applied shock wave in water at about 2.56 mm above the focus position.

Shock wave – single bubble interaction

A shock wave is made arriving at the position of a single bubble with free collapse time of about 225 µs at two different moments of its oscillation cycle. In Figure 5 the shock impinges on the bubble at 215 µs after optical breakdown. Interframe time is 1 µs, the frame width, 1.44 mm. The shock is propagating from bottom to the top and the laser beam comes from the right-hand side. The forced collapse is visible in the second frame which corresponds to the time about 218 µs after laser breakdown. Thus, the interaction with the shock leads to a reduction of the collapse time of about 7 µs. After collapse, a liquid jet is formed in the direction of shock propagation [7].

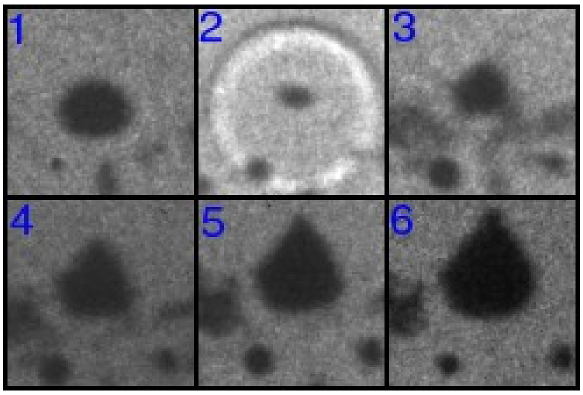

Figure 5: Forced collapse of a single bubble exposed to a lithotripter shock wave. The interframe time is 1 µs, the frame width is 1.44 mm. A liquid jet is generated in the direction of the shock wave propagation and the collapse time is also reduced compared to the free oscillation.

In Figure 6 the shock wave arrives at the collapsing bubble 210 µs after the laser breakdown. The first frame is taken at about 216 µs after breakdown, immediately after the bubble has collapsed. In this case, the reduction of collapse time amounts to about 9 µs. It is because the bubble size at the time of shock arrival is slightly larger and a larger bubble needs more time in order to collapse. It becomes experimentally more difficult to achieve a further reduction of collapse time by applying the shock sooner, because the tension wave of the tail of the shock starts to expand the bubble, and thus counteracts the effect of the shock itself.

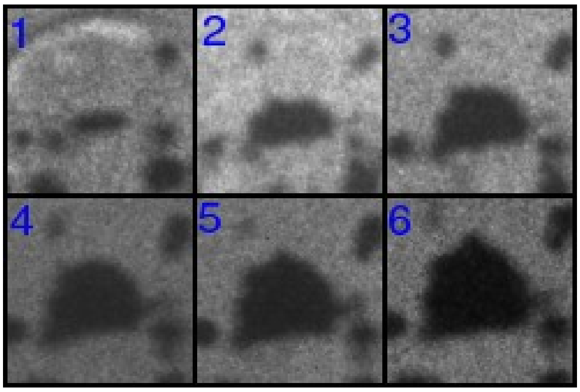

Figure 6: Forced collapse of a single bubble exposed to a lithotripter shock wave. Interframe time is 1 µs and frame width being 1.44 mm.

Conclusions

Due to the presence of a shock wave, the bubble collapse is asymmetric and a jet is formed in the direction of the shock wave propagation. The collapse time is also reduced compared to free oscillation. The collapse shock is amplified by the applied shock wave. The tension phase of the lithotripter shock wave produces some secondary cavitations. These cavitations should be minimized in the study of single bubbles, but they provide a good opportunity to study the dynamics of bubble clouds. These bubbles are not visible in the absence of a shock wave.

Acknowledgments

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