Dynamics of attached cavitation at an ultrasonic horn tip

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Introduction

Ultrasonic horn transducers – also called sonotrodes or disintegrators – are frequently used in applications of acoustic cavitation in liquids, for instance for cell disruption or sonochemical reactions. They are operated typically in the frequency range up to about 50 kHz and have tip diameters from some mm to several cm. If the horn tip is sufficiently small and driven at high amplitude, cavitation is very strong, and the tip can be covered entirely by the gas/vapour phase for longer time intervals, which actually interrupts the horn-liquid contact. From acoustic emission spectra and high-speed photographic recordings, a peculiar dynamics of this attached cavitation sheet in front of the tip can be observed. In particular, expansion and collapse can be subharmonic with respect to the driving frequency. The gas/vapour phase can appear in a mushroom shape and split or eject a larger cluster which violently collapses below the tip. Here, we show some experimental observations of the cavitation zone below a tip of 3 mm diameter, driven at 20 kHz. For modeling purposes, a hydrodynamic cavitation code is employed.

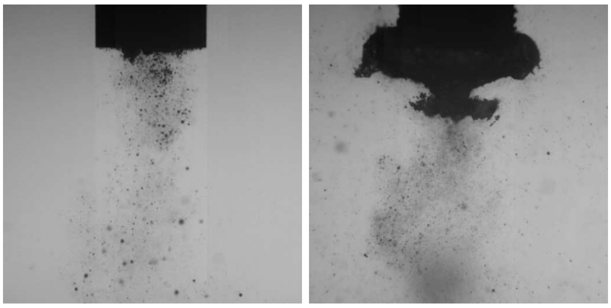

Figure 1: Tip of ultrasonic horn in tap water (short term exposure of 1 μs). Power settings on 10% (left) and on 50% (right), respectively.

Experimental high-speed observations

The sonotrode tip of a Branson Sonifier (20 kHz, tip diameter 3 mm) in a Hellma 5x5x5cm^3 cubic glass cuvette with non-degassed tap water at room temperature (1 cm dipping depth) was monitored with a Photron APS-RX high-speed camera at various speeds and magnifications (back lighting). Figure 1 given an impression of the structural changes when the power setting was increased from the smallest value (10%) to the maximum allowed (50%). At low power, there exists only a small attached gas sheet below the tip, covering from virtually nothing up to about one half of the tip, depending on the oscillation phase. Below the horn, a slightly diverging zone of individual smaller bubbles around the symmetry axis is formed. At high power (and after transients), the tip is almost always covered entirely by the gas/vapor phase in form of a big attached bubble. The bubbly zone below seems to be higher populated than at lower power, and it develops a Kelvin-Helmholtz-like instability (waves) while streaming downwards. A peculiar dynamics of the large attached bubble is found: expansion and collapse take place on subharmonic (slower than driving) time scale, and the bubble form changes characteristically from “mushroom” to “cone” before collapse; see Fig. 2. This behaviour is not limited to the specific horn system employed, but was also observed at other sonotrodes and higher frequencies of 25 kHz and 47 kHz [1]. The subharmonic emission from the big bubble falls mostly into the range of 1/7 to 1/5 of the driving, and it can even exceed the fundamental peak in the acoustic spectrum [1]. This subharmonic component is typically not strongly present in other acouostically cavitating systems [2].

Numerical study

The big attached gas/vapor phase at the sonotrode tip has some features in common with other cavitation phenomena observed in hydrodynamic systems. Namely, the large attached area and the apparently “self-generated” (subharmonic) oscillatory behavior appear for example in unsteady cavitation at hydrofoils [3]. Therefore, we tried to siumulate the gas/vapor phase dynamics with a commercial hydrodynamic cavitation code (FLUENT [4]). Preliminary results are shown in Fig. 3 in comparison to experimental frames. While these results can partly indeed capture the subharmonic dynamics, and thus are encouraging, they document as well a present shortcoming of the code. Nucleation rate parameters had to be set on very high (far from standard) values to best match the observations.

It can be seen that development of cavitation in the simulation is much faster than in the experiment (see Fig. 4). But the main difference is that after each collapse in the simulation, there is practically no vapor left in the domain. In the experiment, the amount of vapor and non dissolved gasses after collapse rises in time and has dramatic effects on the development of cavitation.

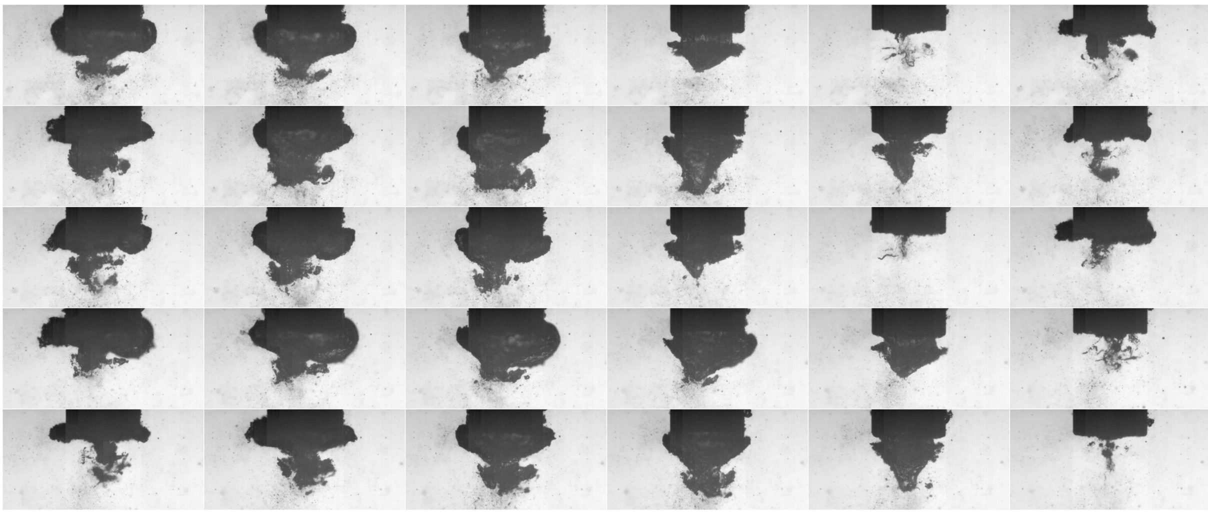

Figure 2: Sequence from a high-speed recording of the tip at 50% power setting (20000 frames/sec; exposure 1 μs; from left to right, first row comes first). Each driving period, one frame is taken, and the arrangement in the picture reveals an attached bubble dynamics with a repetition after about 6 driving periods.

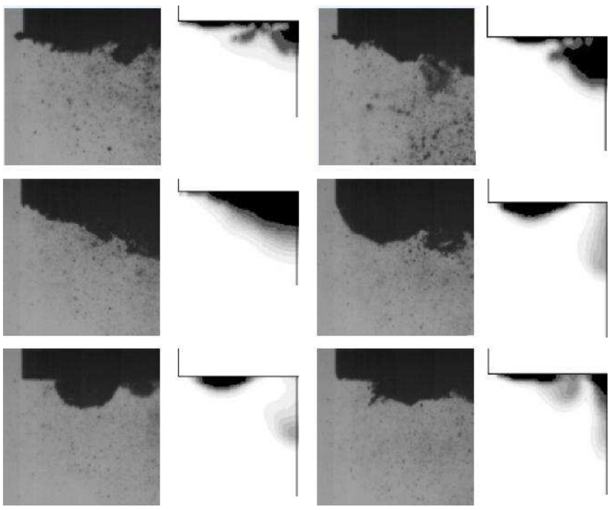

Figure 3: Comparison of numerical gas/vapor distribution (dark) with frames from the experimental recording (visible area: edge of the tip to symmetry axis). First row: beginning of attached bubble cycle. Middle row: attached bubble when gas/vapor amount is largest. Bottom row: Collapse phase of attached bubble.

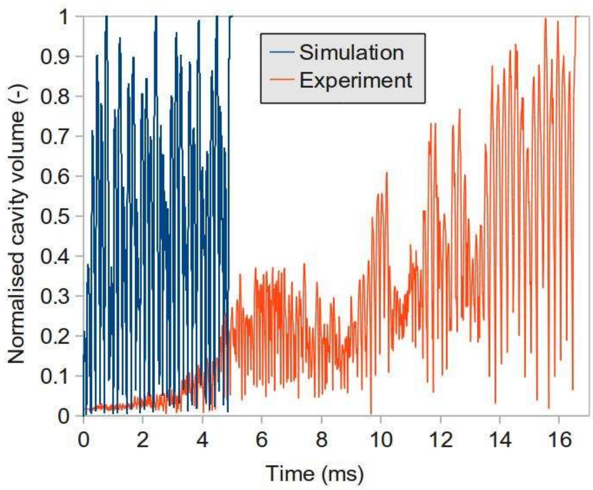

Figure 4: Comparison of the normalised volume of gas/vapor phase in front of the tip vs. time during the transient phase after power on (experiment red, simulation blue).

Conclusions

We have documented a peculiar dynamics of an attached big bubble at an ultrasonic horn tip. The first results of numeric modeling employing a commercial hydrodynamic cavitation code are promising, although they seem to be indication of the "convective" nature of standard hydrodynamic problems (the liquid passes only once the cavitating body). In acoustic set-ups like the sonotrode system, we have rather a "resident" nature of the problem, and the bubble (and thus nuclei) population can develop in time. In particular, bubbles (and total gas/vapor phase) grow in time, i.e. have a longer transient, as visualized in Fig. 4. Future research will try to modify the numerical code sufficiently and record additional data for a better understanding of developed attached cavitation in acoustic systems, like in the presented case of a strongly driven small diameter sonotrode tip.

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References

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