ČESKÁ AKUSTICKÁ SPOLEČNOST

CZECH ACOUSTICAL SOCIETY

19. – 21. května 2009

Experimental study of strong pressure pulses radiated by oscillating spark bubbles

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Abstract Pressure pulses radiated by spark generated bubbles are examined with an aim to determine whether shock fronts developed in them. A rise time of a leading edge of the pressure pulse is used as a suitable indicator of the shock front presence. Only pressure pulses radiated by bubbles having maximum radii of approximately 45 mm are considered. It has been found that for moderate intensities of bubble oscillations ($p_{zp1} < 90$) no shock fronts developed in the pressure pulses. However, if the bubbles oscillate with a sufficiently high intensity ($p_{zp1} > 90$) the rise time becomes as short as 1 μs, indicating that the limits given by the hydrophone are reached. The procedure used in this study does not allow determining if the pressure pulse deformation is due to finite amplitude wave effects or due to shock front presence. To resolve this question new experiments are being prepared.

1 INTRODUCTION

Oscillations of cavitation bubbles can be extremely intensive. During these intensive oscillations narrow steep pressure pulses (spikes) are radiated, with very high peak values. In the literature it is common to refer to these pulses as shock waves. But are these pulses really always shock waves? Shock waves, such as those generated in shock tubes or in underwater explosions can be characterized by a very steep shock front which propagates with a supersonic velocity. However, as we have examined recently a large number of recorded pressure waves radiated by spark generated bubbles with an aim to find the shock fronts in them, we were surprised at not finding fully convincing proofs of the presence of shock fronts in these waves. Results presented here are an extension of the work published in reference [1].

2 EXPERIMENTAL SETUP

The conclusions reported here are based on a large number of experiments, in which freely oscillating bubbles have been generated by discharging a capacitor bank via a sparker submerged in water. The discharges took place in a laboratory water tank having dimensions 6 m x 4 m x 5.5 m. The experimental setup is schematically shown in Figure 1 and a detailed description of it can be found in reference [2].

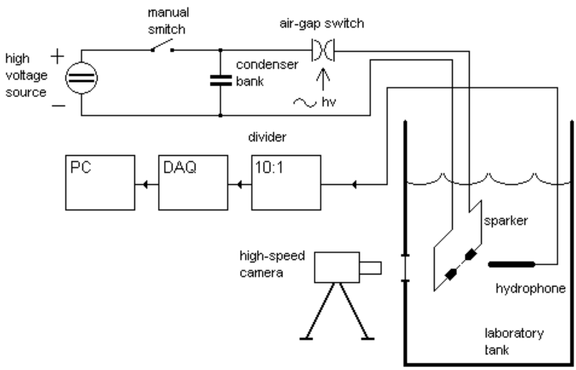

Figure 1. *Experimental setup used to study spark generated bubbles*

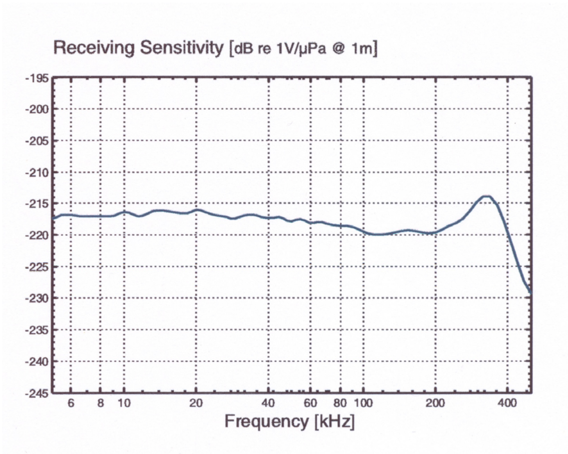

Figure 2. *Frequency response of the hydrophone TC 4034*

The pressure waves radiated by the bubbles were recorded with a broadband hydrophone (Reson type TC 4034) having a usable frequency range from 1 Hz to 470 kHz. The frequency response of the hydrophone is shown in Figure 2. The hydrophone was positioned at distances from the bubble center r = 0.1 m, 0.25 m, and 0.5 m. The hydrophone output was connected via a voltage divider to a data acquisition board (National Instruments PCI 6115, 12 bit A/D converter) having a sampling frequency of 10 MHz. The experimental bubbles could be recorded using a 16-mm film rotating prism high-speed camera.

3 PRESSURE RECORDS

Altogether 950 pressure wave records have been obtained. Using a suitable filtering procedure [3] it was verified that the hydrophone's bandwidth was sufficient for a reliable recording of the majority of the pressure waves. An example of a pressure record is given in Figure 3.

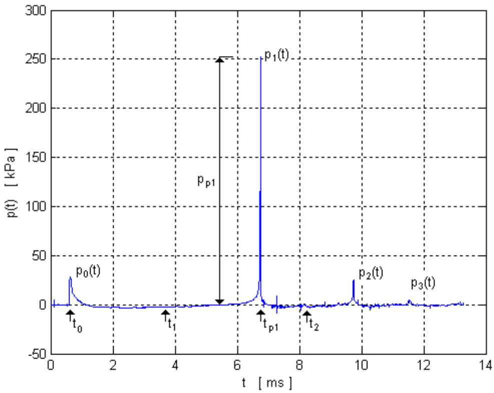

Figure 3. *A pressure wave radiated by an oscillating spark generated bubble at r = 0.1 m*

A freely oscillating spherical bubble is described by its size and intensity of oscillations. A suitable measure of the bubble size is the first maximum radius R_{M1}. This quantity can be easily determined from a pressure record using a formula:

$$R_{M1} = \frac{T_{o1}}{2T_{zc1}\sqrt{\dfrac{\rho_\infty}{p_\infty}}} \quad .$$

Here T_{o1} is a time of the first bubble oscillation, ρ_∞ is liquid density, p_∞ is ambient pressure in the liquid at the place of the bubble and T_{zc1} is a non-dimensional time of the first bubble compression.

A suitable measure of bubble oscillation intensity is the non-dimensional peak pressure in the first bubble pulse p_{zp1} defined by equation

$$p_{zp1} = \frac{p_{p1}}{p_\infty}\frac{r}{R_{M1}} \quad .$$

Here p_{p1} is a peak pressure in the first bubble pulse and r is the distance from the bubble center to the hydrophone.

From the pressure records we were able to determine for each bubble its size, as represented by a maximum bubble radius, R_{M1}, and intensity of oscillations, as represented by a non-dimensional peak pressure in the first bubble pulse, $p_{zp1.}$ The bubble sizes R_{M1} and bubble oscillation intensities p_{zp1} determined in this way are summarized in the bubble map shown in Figure 4.

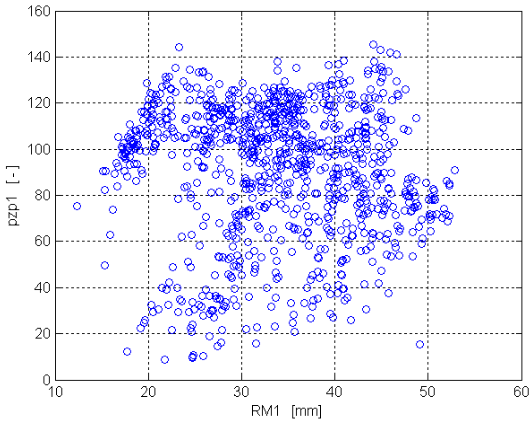

Figure 4. *The bubble map for experiments with spark generated bubbles*

It can be seen that the generated spark bubbles were relatively large (R_{M1} ranging from 12 mm to 53 mm) and oscillating with a broad range of intensities (p_{zp1} ranging from 9 to 145). Comparable intensities have also been reported in literature [4].
The broad range of bubble oscillation intensities and the large bubble sizes have proved to be essential in the present study. The large bubbles radiate pressure waves, the energy content of which is concentrated at lower frequencies first of all. And the lower frequency components can be transmitted by the available hydrophone reliably. Should there be a shock front in a wave, then this shock front is composed of components having very high frequencies. In this case the shock front cannot be recorded reliably with our apparatus. The hydrophone will act as a low pass filter with the upper cut off frequency being approximately 500 kHz and thus all pulses with the true rise time shorter than 1 μs will appear at the output of the hydrophone as pulses with the rise time of approximately 1 μs. And because of this it will be not possible to discriminate between an ordinary shock front, a degenerated shock front or a very steep but finite amplitude pressure pulse.

Our search for the shock fronts is based on exploiting a large range of bubble oscillation intensities occurring in our experiments. It can be expected that no shock fronts are present in the pulses radiated by bubbles oscillating with low intensities. However, if we are examining waves radiated by bubbles which oscillate with gradually increasing intensities, then at a certain level we should arrive at the above mentioned limiting rise time, beyond which the existence of the shock fronts can be presumed, but not proved. To check the reliability of our measurement, we are observing not only the rise time of the pulses, but also the energy spectra of the pulses.

4 A SEARCH FOR THE SHOCK FRONTS

In the way mentioned above many records have been examined, corresponding to bubbles oscillating with gradually increasing intensities. All examined pressure records have been radiated by bubbles having sizes approximately $R_{M1} \approx 45$ mm, which is ensuring that all important frequency components lie in the frequency band-pass of the hydrophone. As an illustrative example a few selected records and their corresponding energy spectral densities are given in Figs 5 – 8 ordered with increasing intensity of bubble oscillation. A pressure pulse radiated by a bubble oscillating with a relatively low intensity is shown in Figure 5. A pressure pulse radiated by a bubble oscillating with an intensity being immediately below the 1 μs limit is given in Figure 6. A pressure pulse radiated by a bubble oscillating with an intensity being immediately above the 1 μs limit is given in Figure 7. And finally a pressure pulse radiated by a bubble oscillating with a high intensity is given in Figure 8.

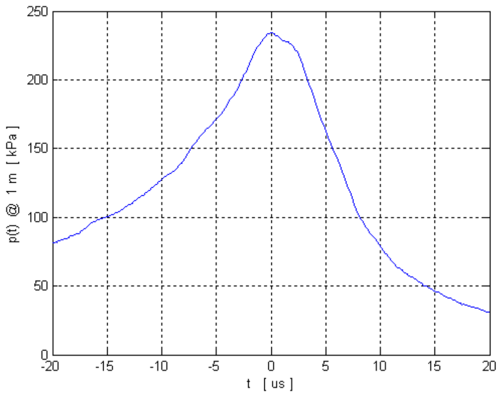

Figure 5a. *A detailed view at the first bubble pulse*

(RM1 = 44.65 mm, pzp1 = 41.92)

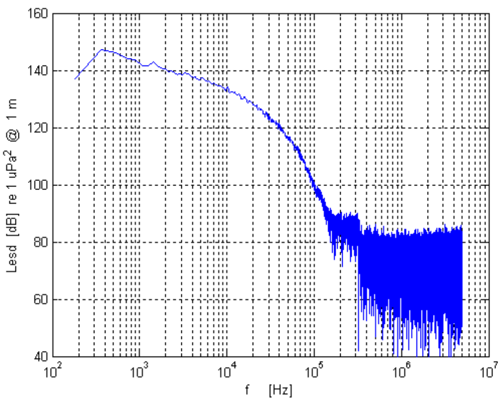

Figure 5b. *Energy spectral density of the first bubble pulse*

(R_{M1} = 44.65 mm, p_{zp1} = 41.92)

A detailed view at the pressure pulse radiated by a bubble oscillating with relatively low intensity is given in Figure 5a. There is no sign of a shock front presence in the pulse. As can be seen in Figure 5b, all spectral components lie well below the hydrophone limiting frequency.

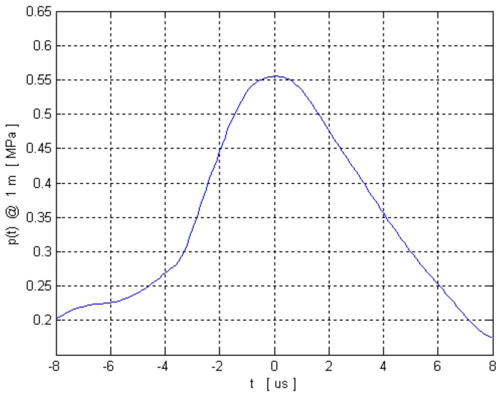

Figure 6a. *A detailed view at the first bubble pulse*

(R_{M1}= 52.24 mm, p_{zp1} = 85.11)

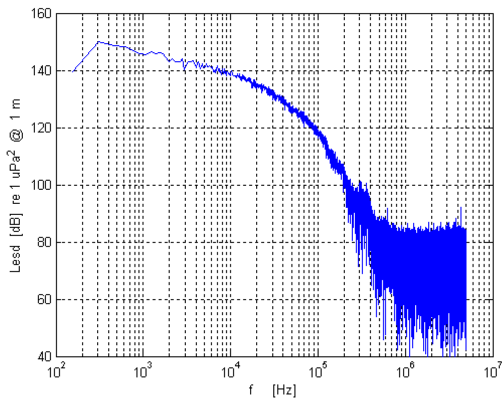

Figure 6b. *Energy spectral density of the first bubble pulse*

(R_{M1} = 52.24 mm, p_{zp1} = 85.11)

The rise time of the leading edge of the pressure pulse shown in Figure 6a is approximately 2 µs, thus no filtering due to the hydrophone is present. As can be seen in Figure 6b, all spectral components lie below the hydrophone limiting frequency again.

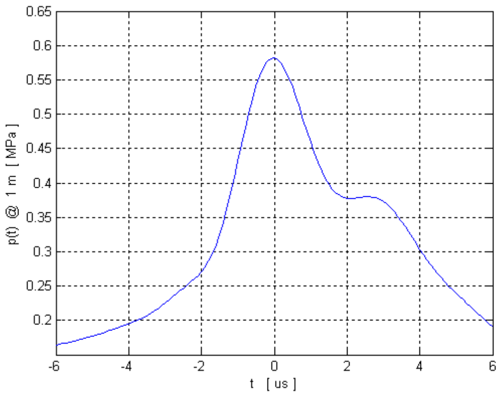

Figure 7a. *A detailed view at the first bubble pulse*

(R_{M1} = 46.98, p_{zp1} = 97.52)

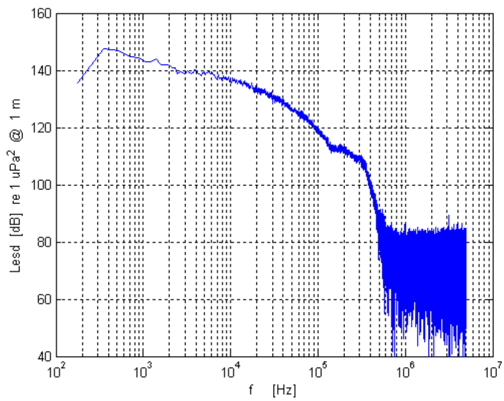

Figure 7b. *Energy spectral density of the first bubble pulse*

(R_{M1} = 46.98, p_{zp1} = 97.52)

The rise time of the leading edge of the pressure pulse shown in Figure 7a is approximately 1 μs, thus some filtering due to the hydrophone may be present. However, even now, as can be seen in Figure 7b, all spectral components lie below the hydrophone limiting frequency.

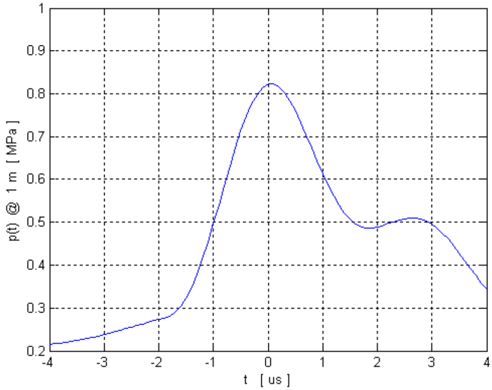

Figure 8a. *A detailed view at the first bubble pulse*

(R_{M1} = 46.63 mm, p_{zp1} = 141.29)

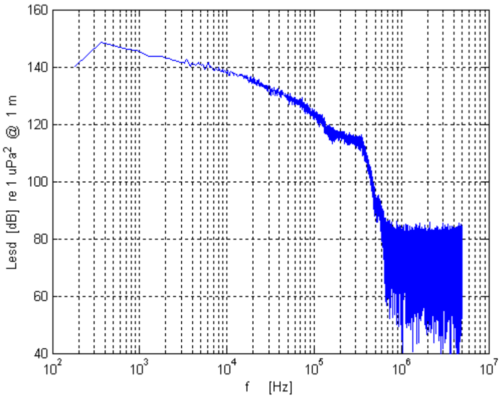

Figure 8b. *Energy spectral density of the first bubble pulse*

(R_{M1} = 46.63 mm, p_{zp1} = 141.29)

The rise time of the leading edge of the pressure pulse shown in Figure 8a is approximately 1 µs, thus some filtering due to the hydrophone is most probably present. Some filtering due to the hydrophone can also be seen in Figure 8b.

5 CONCLUSIONS

An analysis of a large set of pressure waves radiated by spark generated bubbles has been carried out with the aim to detect the presence of shock fronts in the first bubble pulses. Even if the measured pulse profiles can be interpreted in some cases as being shock fronts filtered by the hydrophone, no convincing evidence for the presence of the shock fronts has been found yet. However, this does not exclude the possibility, that, when observing bubbles oscillating with even higher intensities than in our experiments, and using a hydrophone with sufficiently wide bandwidth, the shock fronts could be finally detected convincingly.

Results of the search for the shock fronts described in this work (for bubbles sizes approximately $R_{M1} \approx 45$ mm) can be summarized as follows. For $p_{zp1} < 90$, no shock waves were observed. For $p_{zp1} > 90$ there might be shock fronts but further experiments are needed to verify this.

ACKNOWLEDGMENTS

This work has been partly (K. V.) supported by the Ministry of Education of the Czech Republic as the research project MSM 467 478 8501.

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