

Experimental Study of the Bubble Pulse

Experimentelle Untersuchung von Blasenimpulsen

Etude expérimentale de l'impulsion émise par une bulle

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1. Introduction

Due to the random nature of cavitation, direct observations of cavitation bubbles, and the pressure waves (bubble pulses) radiated during their oscillations, are extremely difficult. Therefore, in experiments, the cavitation bubbles are often substituted by spark generated bubbles (see, e.g. reference [1]). Spark generated bubbles can be produced at an exactly defined place and time which strongly facilitates their observation. Over the last fifteen years laser generated bubbles have also been successfully employed in bubble dynamics studies (see, e.g. reference [2]). In the present research note these bubbles are exploited to study the bubble pulses.

2. Experimental arrangement

An experimental set-up for the bubble pulse measurement is sketched in Fig. 1. A pulsed ruby laser with a beam diameter of about 10 mm, a pulse duration of about 30...50 ns, and a total pulse energy of about 0.1 J served as a source of intense light pulses. These pulses were focussed into a container filled with distilled water by means of a lens having a focal length of 20 mm in air. The container had a form of a cube with an inner edge length of 0.1 m. The lens was situated just outside the container.

The bubbles and pressure waves produced in the focal point of the lens were diffusely illuminated by a flash lamp

through a ground-glass plate and photographed by an image converter with a framing rate of one million frames per second. A hydrophone for picking up the bubble pulses was inserted into the water from above and oriented perpendicular to the direction of the laser beam. The hydrophone distance from the focal point was varied from 8 mm to 30 mm during the tests. (The hydrophone design and calibration are described in reference [3].) A signal from the hydrophone was fed via a coaxial cable to an oscilloscope. The screens of the image converter and of the oscilloscope were simultaneously photographed by two Polaroid cameras.

3. Results

Photographs from the image converter were used to check the bubble form and behaviour at the initial stages only. Therefore, the maximum bubble radius, R_{M1} , was determined from Rayleigh's formula for the collapse time, T_{c1} , of an empty bubble [4]

$$\frac{T_{o1}}{2} = T_{c1} = 0.915 R_{M1} \sqrt{\frac{\rho_{\infty}}{p_{\infty}}} \quad (1)$$

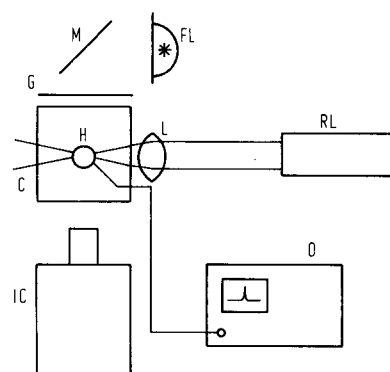


Fig. 1. Experimental set-up for bubble pulse examination. RL – ruby laser, L – lens, FL – flash lamp, M – mirror, G – ground-glass plate, C – container, H – hydrophone, IC – image converter, O – oscilloscope.

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Here T_{o1} is the time of the first bubble oscillation (which can be determined from the time of the bubble pulse occurrence on the oscilloscope screen), $\rho_\infty = 10^3 \text{ kg m}^{-3}$ is the water density, and $p_\infty = 100 \text{ kPa}$ is the ambient pressure in the liquid. As the times of the first bubble oscillations, T_{o1} , ranged from 240 to 300 μs , it follows from eq. (1) that the first maximum bubble radii, R_{M1} , ranged from 1.3 to 1.65 mm.

An example of the measured bubble pulse is given in Fig. 2. Because of the signal distortion at later stages (due to reflections in the hydrophone), only the leading edge of the pulse could be studied. As indicated in Fig. 2, the leading edge can be roughly divided into two parts. In part I the pressure in the wave grows relatively slowly. To a first approximation this growth can be considered to be exponential with a time constant, ϑ'_1 , the value of which ranged from 0.75 to 1.35 μs . Approximately 35...45% of the total acoustical energy associated with the leading edge of the bubble pulse can be ascribed to this region.

In part II the growth of the pressure in the wave is much steeper: during a time interval of 0.1...0.15 μs the pressure grows to a value which is about three times higher than the

value the wave had at the end of part I. Approximately 55...65% of the total acoustical energy of the pulse leading edge can be associated with this part. Unfortunately, because of the time resolution used it was not possible to determine whether this part of the pulse represents a degenerated shock wave or an ordinary (though very steep) pressure wave.

From the measured pressure vs. time records, $p(t)$, the effective width of the pulse leading edge, ϑ'_1 , could be determined from the formula [4, 5]

$$\vartheta'_1 = \frac{1}{p_{p1}^2} \int_a^b p^2(t) dt. \quad (2)$$

Here p_{p1} is the peak pressure in the bubble pulse; the lower limit of integration, a , corresponds to the beginning of part I, and the upper limit of integration, b , to the end of part II. Integration was performed numerically using approximately 10 unequally spaced values of the pressure $p(t)$. (These values were taken from enlarged photographs of the bubble pulses.) The values of ϑ'_1 obtained in this way ranged from 0.1 to 0.15 μs . Note that to determine ϑ'_1 , no knowledge of the absolute values of the pressure $p(t)$ is required. This may be a convenience in those situations where the absolute hydrophone sensitivity is unknown.

From the measured values of ϑ'_1 and R_{M1} a non-dimensional effective width of the bubble pulse leading edge, ϑ'_{z1} , can be determined using the formula [4, 5]

$$\vartheta'_{z1} = \frac{\vartheta'_1}{R_{M1} \sqrt{\frac{\rho_\infty}{p_\infty}}}. \quad (3)$$

The effective widths, ϑ'_{z1} , found in this way ranged from 0.6×10^{-3} to 1.3×10^{-3} . These values allow for direct comparison with the theoretical scaling functions $\vartheta'_{z1} = \vartheta'_{z1}(A_1, \gamma)$ as displayed in Fig. 3. Here $A_1 = R_{M1}/R_e$ is the amplitude of the first bubble oscillation [4, 5], R_e is the "equilibrium" bubble radius, and γ is the polytropic exponent for the bubble content (vapour).

The scaling functions $\vartheta'_{z1} = \vartheta'_{z1}(A_1, \gamma)$ displayed in Fig. 3 were computed using a procedure that is described in great detail in reference [5]. Note that $\vartheta'_{z1} > \vartheta'_{z1}/2$ for larger A_1 . (Here ϑ'_{z1} is the effective pulse width encompassing both the leading and trailing pulse edges; the scaling functions $\vartheta'_{z1} = \vartheta'_{z1}(A_1, \gamma)$ were given in reference [5]).

From Fig. 3 it can be seen that the amplitudes A_1 , corresponding to the effective widths given above, range from 3.0 to 3.5 ($\gamma = 1.25$) and from 3.25 to 3.7 ($\gamma = 1.33$). These values agree well with the values of A_1 determined for spark generated bubbles in reference [5] where it was found that $A_1 = 3.29$ ($\gamma = 1.25$) and $A_1 = 3.5$ ($\gamma = 1.33$).

4. Conclusion

The method described above makes it possible to determine the amplitudes of bubble oscillations even with an uncalibrated hydrophone. The procedure can easily be extended to measure the damping factors of bubble oscillations [5]. In cases where a calibrated hydrophone is available, a third important quantity, the peak pulse pressure, can also be determined. These three parameters together with the bubble size (which can be conveniently determined from eq. (1)) constitute a sufficient base for detailed investigation of the bubble behaviour [5].

The amplitudes found in this study are approximately the same as those established in reference [5]. Thus the present measurements corroborate those earlier results. However, to

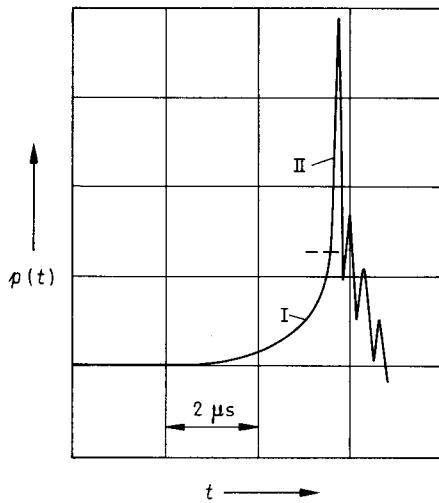


Fig. 2. Example of the measured bubble pulse.

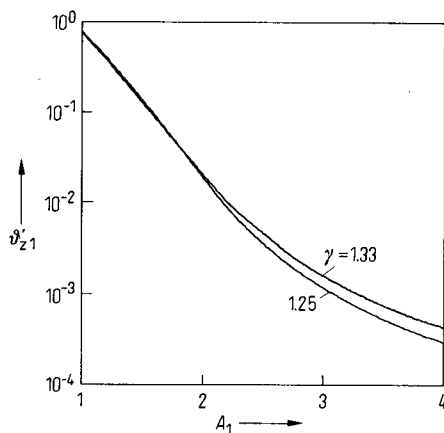


Fig. 3. Theoretical scaling functions $\vartheta'_{z1}(A_1, \gamma)$.

some extent this is rather a surprise as one would have expected slightly lower amplitudes (due to thermal losses) for the bubble sizes generated in this study [6].

Acknowledgements

The experimental part of the present piece of research was carried out on the apparatus of Prof. W. Lauterborn during the author's stay at the Third Physical Institute of the University of Göttingen. The hydrophone employed was designed and produced by Dr. U. Radek. Last but not least, the author wishes to thank to Dr. K. Kuhnke for his valuable help at the experimental stage.

(Received November 5th, 1987.)

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