

# THE USE OF A SHOCK TUBE IN BUBBLE DYNAMICS STUDIES

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Received 10 May 1991

Oscillations of gas bubbles in a liquid are studied using a shock tube. Beside observing the bubble wall motion with the help of a camera, a pressure wave field in the liquid is investigated in detail. The rise time of the driving pressure step turns out to be rather large. This pressure step is also accompanied by a precursor whose origin is still unclear. The waves propagating into the liquid behind the pressure step appear to be strongly disturbed; clean waveforms can be obtained only in the immediate vicinity of the bubble. Examples of several waveforms recorded this way are presented.

## 1. Introduction

When a shock wave passes a gas bubble in a liquid, the suddenly increased pressure in the liquid will cause an oscillation of the bubble. Such an excitation of the bubble for free oscillations can be conveniently used in laboratory studies concerning bubble dynamics. The shock waves used in these experiments can be generated by underwater explosions [1], by underwater electric discharges (sparks) [2, 3], or by a shock tube [4 - 7].

Here experiences with the last method, i.e. with the bubble excitation in a shock tube, are reported. Whereas in Refs. [4-7] the emphasis was laid on photographic investigation of bubble dynamics we have gone a step further and encompassed a detailed study of the pressure waves radiated by oscillating bubbles as well. This was made possible by using a recently developed needle hydrophone [8, 9]. In the following paper the shock tube and the associated apparatus are described in detail. Also several waveforms radiated by oscillating bubbles are presented.

## 2. Experimental setup

The experimental apparatus used for studies of gas bubble dynamics is schematically shown in Fig. 1. Main feature of the apparatus is a vertical shock tube (total length 4 370 mm) consisting of three sections:

- The high pressure section, which is to be filled with the driver gas (nitrogen) at a pressure  $p_4$ . This pressure can be varied from 0.1 to 2.4 MPa.
- The low pressure section, which is normally filled with air of ambient pressure ( $p_1 = 0.1$  MPa).
- The last (and lowest) section containing the working liquid, which is filled from a supply container, whose height with respect to the tube end wall can be varied (thus controlling the level of the liquid).

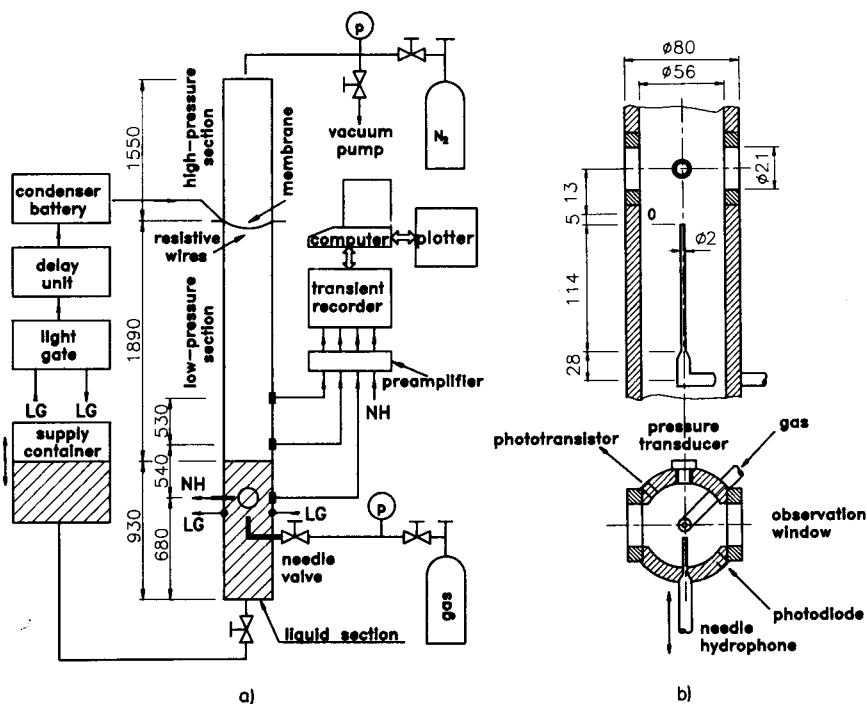


Fig. 1. Experimental apparatus for bubble dynamics studies with the use of the shock tube: a) general view (NH – needle hydrophone, LG – light gate), b) detail of the shock tube working section.

To prevent formation of undesirable bubbles the liquid was filled in very slowly (approximately for 30 minutes). Tap water was used as a working liquid for preliminary experiments. However, most of the work was done with diluted glycerine (85%  $C_3H_8O_3$ ).

The high- and low-pressure sections were separated by a hostaphane diaphragm of thickness  $h$ . This thickness  $h$  was selected in such a way as to ensure sufficient diaphragm sagging and stressing at a given pressure  $p_4$ . The sagged diaphragm touched two resistance heating wires (Cronix 80 E,  $\varnothing$  0.3 mm) stretched below the diaphragm in a cross. When a condenser battery (600  $\mu$ F, 200 V) was discharged across the resistance wires the stressed diaphragm melted and tore along the contact line with the wires. Thus, the moment of shock wave initiation could be set very precisely.

The following empirical relation was found to be valid between high pressure  $p_4$  and diaphragm thickness  $h$ :

$$h[\text{mm}] = 0.125 p_4[\text{MPa}].$$

It follows from this relation that the suitable diaphragm thickness ranged from 0.0125 to 0.3 mm.

The bubbles were generated by a small L-shaped tube submerged in the liquid. The inner and outer tube diameters were 1.8 and 2 mm, respectively, and the upper end of the tube was slightly conic. It was carefully checked (by comparing the pressure waveforms recorded with and without the submerged tube) that the presence of the tube produced no distortion of the measured waveforms. The gas from the bottle was supplied to the L-tube via reducing and needle valves. A steady train of the gas bubbles was generated at the conic end of the tube. The time interval between two consecutive bubbles was usually set between 3 and 5 s. Two gases were used for the bubbles: (1) nitrogen, and (2) a mixture of a detonating gas with argon, i.e. 30% ( $2\text{H}_2 + \text{O}_2$ ) + 70% Ar.

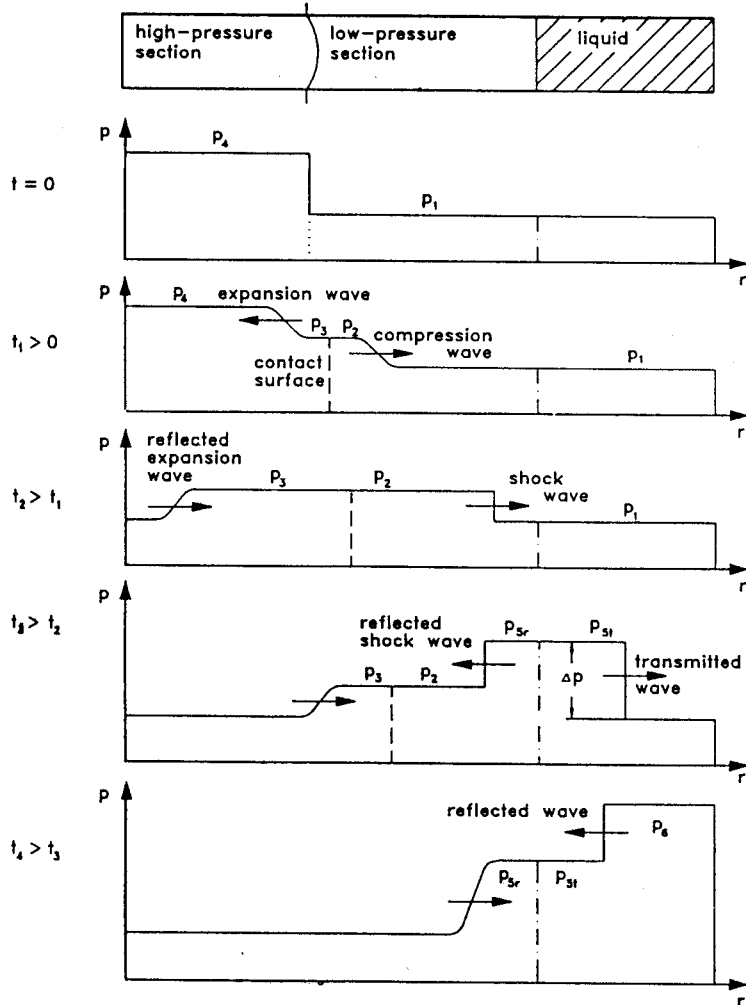


Fig. 2. Pressure distribution in the shock tube for selected time instants ( $p-r$  diagram).

The generated bubbles rose with a velocity of about  $0.2 \text{ m s}^{-1}$  in water and  $0.06 \text{ m s}^{-1}$  in glycerine. The bubble radius  $R_i$ , which was determined from photographs, was found to be fairly well reproducible (in glycerine  $R_i = 1.65 \pm 0.1 \text{ mm}$ ). The rising bubble interrupted a beam of a light gate (formed by a photodiode, phototransistor and associated electronics). The gate sent off a pulse which after a preset retardation in a delay unit triggered the condenser battery discharge. After the diaphragm was torn up a shock wave propagating downwards was formed in the low-pressure section. At the liquid surface the shock wave was partially reflected and partially transmitted into the liquid, where the wave continued to propagate downwards. After reflecting at the bottom, the wave traversed the liquid again and reflected again at the liquid surface. This process was repeated several times before the wave was completely attenuated. The formation of the shock, expansion and pressure waves in the shock tube is schematically shown for several time instants in Fig. 2.

Time histories of the pressure waves in the liquid and in the gas were obtained by several suitably positioned pressure transducers (PCB type 113 A 24). Examples of the recorded pressure vs. time histories in the gas and in the liquid (in this case in water) are given in Fig. 3. In Figs. 3a and 3b one can see a forward propagating shock wave, a reflected shock wave and a reflected expansion wave picked up at two different transducer positions in the gas (cf. Fig. 1a). In Fig. 3c a corresponding pressure vs. time record in the liquid is shown.

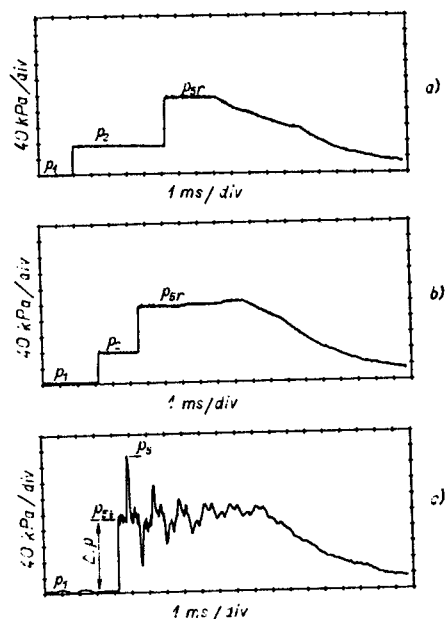


Fig. 3. Examples of the recorder pressure vs. time histories for  $p_4 = 250 \text{ kPa}$ : a) and b) pressure records in the gas, c) pressure record in the liquid without a bubble.

As mentioned above, in the liquid the pressure wave is successively reflected at the solid bottom and at the free liquid surface. The propagation of the pressure wave in the shock tube and corresponding pressure vs. time history at the location of the transducer in the liquid is schematically given in Fig. 4. A record of the measured waveform in the liquid has already been presented in Fig. 3c. Another record, which was obtained in glycerine with a higher time resolution, is shown in Fig. 5a. Figure 5b is an enlarged (zoomed) detail of the pressure wave leading edge (the pressure step).

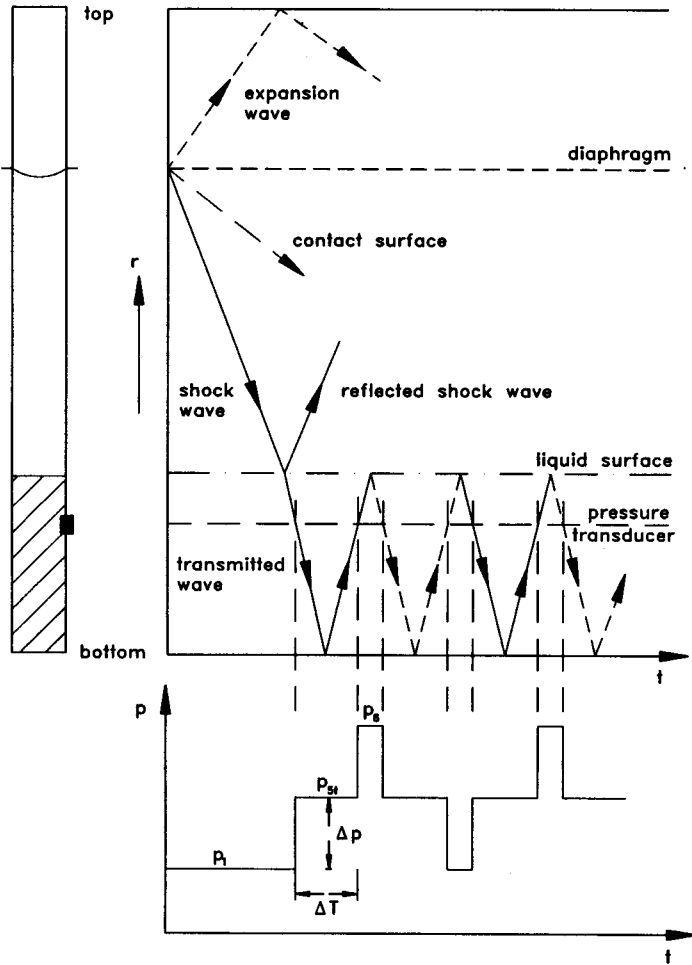


Fig. 4. Wave propagation in the shock tube ( $r-t$  diagram) and a sketch of the pressure vs. time history in the liquid at the place of the transducer.

The period between the arrival of the first transmitted wave and the arrival of the wave reflected from the bottom is most suitable for bubble dynamics studies,

as the pressure in the liquid is almost constant there. It can be seen in Fig. 5a that this constant part of the pressure wave,  $p'_{\infty}$ , lasts approximately for  $\Delta T = 750\mu\text{s}$ . For experiments with bubbles of initial radius  $R_i = 1.65\text{ mm}$  this time interval  $\Delta T$  proved to be completely sufficient. Note also in Fig. 5b that the rise time of the pressure wave leading edge is approximately  $\Delta t = 20\mu\text{s}$ . In Fig. 5 two notations are used concurrently; the first one is common in shock wave studies ( $p_1, p_2, \dots$ ), the other in bubble dynamics studies. In the latter case the initial pressure  $p_1$  is denoted as  $p_{\infty i}$  and the transmitted pressure  $p_{5t}$  as  $p'_{\infty}$ . Then

$$p'_{\infty} = p_{\infty i} + \Delta p,$$

where  $\Delta p$  is the pressure step.

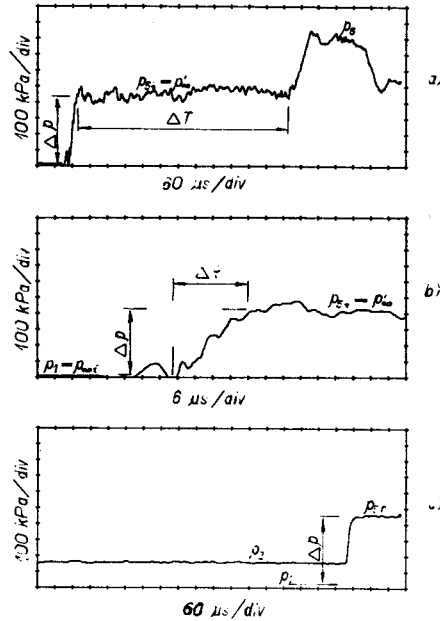


Fig. 5. Examples of the recorded pressure vs. time histories for  $p_4 = 640\text{ kPa}$ : a) pressure wave in the liquid without a bubble, b) an enlarged part of the pressure step leading edge, c) corresponding pressure record in the gas (used to determine the pressure step  $\Delta p$  in the presence of the gas bubbles).

The first experiments were done with water. However, it was found from the bubble photographs that the rising bubbles lose their spherical form and flatten into a lenticular shape. This flattening is in agreement with observations described in the literature [10, 11] and it is interesting that other researchers [4] observed spherical bubbles even in water. In order to obtain spherical bubbles of this size in our experiments, water had to be substituted by glycerine. In glycerine, due to its higher viscosity, the bubbles rise with a lower velocity and thus preserve their spherical shape.

A sketch of the optical apparatus used to photograph the bubbles is given in Fig. 6. A special light source (Nanospark) developed by Miyashiro and Grönig [12] giving light pulses of about 40 ns duration was used here. With this light source, good quality single photographs could be obtained. In experiments without a shock wave, when only the bubble shape, size and rising velocity were studied, the trigger pulse for the Nanospark was taken from a delayed light gate signal. However, when studying the bubble oscillations, the trigger pulse was formed by a delayed output signal of the pressure transducer situated in the liquid.

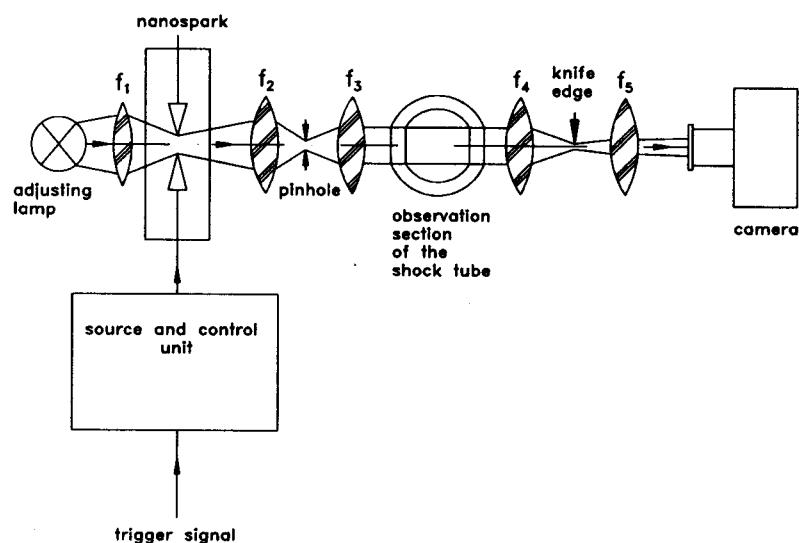


Fig. 6. Optical apparatus used to photograph the bubbles. Focal lengths:  $f_1 = 40$  mm,  $f_2 = 80$  mm,  $f_3 = f_4 = 300$  mm and  $f_5 = 600$  mm.

The pressure wave radiated by the bubble could be picked up both by the PCB transducer at the tube wall and by a needle hydrophone (sensitivity  $K = 5.6$  nV/Pa) developed by Platte [8] and Müller & Platte [9]. The distance hydrophone to bubble center could be varied. To prevent a deterioration of the hydrophone performance it should be submerged in a liquid no more than 5 hours continuously. Therefore it was necessary to transfer the liquid from and to the supply container each day. To remove possible bubbles generated during this transfer, the gas in the upper part of the shock tube was evacuated before the experiments began, and the pressure was kept at 5 kPa for about 10 minutes. However, it seemed that the bubbles were removed not by this decreased pressure but by the following rapid increase of the pressure in the shock tube when the vacuum pump was switched off and the valves opened.

The signals from the pressure transducers and needle hydrophone were fed to preamplifiers (PCB Piezotronics model F 483 A 02 and Kistler Charge Amplifier 5007, respectively). The conditioned signals were then recorded by a transient

recorder (Rene Mauer type TM 509) at a maximum sampling frequency up to 5 MHz and with an amplitude discrimination of 8 bit. The recorded signals were stored on floppy disks for further processing on an Apple II personal computer.

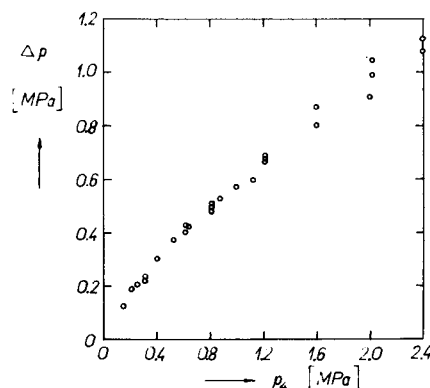


Fig. 7. Experimental values of  $\Delta p$  vs.  $p_4$  in glycerine.

By varying the pressure  $p_4$  from 0.1 to 2.4 MPa it was possible to produce waves in the liquid with pressure steps  $\Delta p$  up to 1.1 MPa (see Fig. 7). As it can be seen in Fig. 7, for a given pressure  $p_4$  the reproducibility of the pressure step  $\Delta p$  was rather poor and it was therefore necessary to measure  $\Delta p$  during each experiment separately. However, at the presence of oscillating bubbles  $\Delta p$  could not be determined directly from  $p_{5t}$  because a wave emitted by the bubble was superimposed. Hence the pressure step  $\Delta p$  had to be measured at the reflected pressure  $p_{5r}$ . The transducer for measuring  $p_{5r}$  was placed immediately above the liquid surface. It was then assumed that the reflected and transmitted waves are equal, i.e.  $p_{5r} = p_{5t}$ . The procedure used for determination of the pressure  $p_{5r}$  (and thus also for  $\Delta p$ ) is shown in Fig. 5c.

### 3. Results and discussion

The first measurements without bubbles showed that there is a considerable difference between the rise time  $\Delta t$  of the pressure step  $\Delta p$  in water and in glycerine. Whereas in water  $\Delta t \approx 5\mu s$  (this value is in a good agreement with other measurements [4, 13]), in glycerine typically  $\Delta t \approx 20\mu s$ . In both cases these values are much larger than the rise time of the shock wave in the gas. Thus the shock wave propagating in the gas and impinging on the liquid surface was not transmitted as a shock wave into the liquid but only as a steep compression wave (see e.g. Fig. 5b).

At the foot of the pressure step a small "ringing" can be seen (see e.g. Fig. 8). The value of the positive part of this "precursor" is directly proportional to the strength of the incident shock wave: it is about one fifth of  $\Delta p$ . Though the origin of this precursor is unclear, it can be assumed that it is generated during the impact of the shock wave on the liquid surface (Müller [13], who also observed this precursor



in the transmitted wave, found that for flat liquid surfaces the amplitude of the precursor was substantially decreased). Because the precursor represents a more violent pressure change than the leading edge of the pressure step itself, it is just this part of the wave one can see on schlieren photographs (see Fig. 9 on Plate I, p. 344a). Thus the precursor can be used as a convenient "zero time mark" both on pressure records and on photographs.

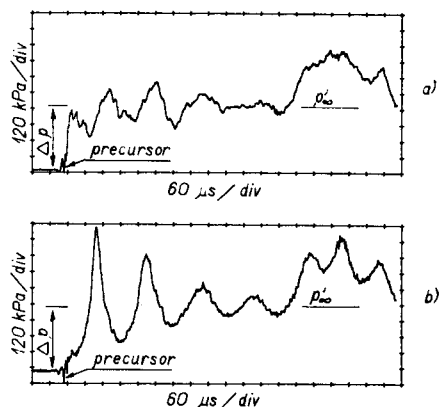


Fig. 8. An example of the records of the pressure waves radiated by an oscillating  $N_2$  bubble in glycerine ( $\Delta p = 480$  kPa): a) signal from a pressure transducer at the shock tube wall ( $r = 28$  mm), b) signal from a needle hydrophone at  $r = 3$  mm.

During the first experiments with oscillating bubbles the pressure waves were monitored only by a PCB transducer situated at the shock tube wall. However, the signals observed were unnaturally distorted (a typical signal from the PCB transducer is given in Fig. 8a). To explain this distortion a needle hydrophone was inserted into the shock tube. The hydrophone holder was designed to allow a variation of the distance  $r$  between the sensitive area of the hydrophone and the center of the bubble from 3 to 28 mm (in the most extreme position  $r = 28$  mm the hydrophone was flush mounted at the shock tube wall). Surprisingly it was found that when the hydrophone was very close to the bubble wall ( $r = 3 - 5$  mm) a "clean" signal could be obtained. However, when increasing the distance  $r$ , the signal became gradually more and more distorted. A comparison of the distorted and clean signals taken during the same experiment is shown in Fig. 8. Therefore all the subsequent measurements were done only for  $r$  ranging from 3 to 5 mm. By photographing the oscillating bubble at different instants of its lifetime it was checked that the presence of the hydrophone in the vicinity of the bubble did not influence the bubble shape (Fig. 10, see Plate I, p. 344a).

The distortion of the pressure waves radiated by oscillating bubbles and propagating through the liquid behind the pressure step is rather unexpected. At first, reflections from the shock tube walls were suspected to be responsible for this distortion. However, the rather erratic pattern of the distorted waves most probably

excludes this mechanism. A more plausible explanation seems to be that after a passage of the steep pressure wave, the acoustical properties of the liquid (e.g. damping) temporarily change in such a way as to chaotically disturb the pressure waves propagating in the medium behind the pressure step. However, further experiments are needed to throw more light on this phenomenon.

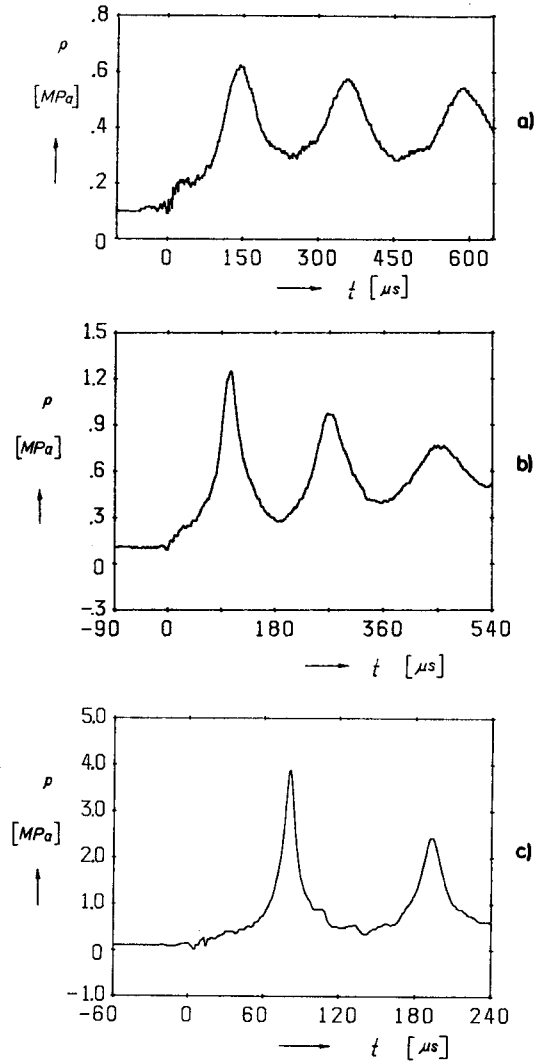


Fig. 11. Examples of the pressure waves radiated by the bubbles oscillating in glycerine ( $r = 3$  mm): a)  $\Delta p = 280$  kPa, gas in the bubble interior: 30% ( $2\text{H}_2 + \text{O}_2$ ) + 70% Ar, b)  $\Delta p = 480$  kPa, gas in the bubble interior: 30% ( $2\text{H}_2 + \text{O}_2$ ) + 70% Ar, c)  $\Delta p = 990$  kPa, gas in the bubble interior:  $\text{N}_2$ .

Several examples of the measured "clean" waveforms emitted by oscillating bubbles are given in Fig. 11. These waveforms were obtained with the needle hydrophone at a distance  $r = 3$  mm away from the center of the bubble. The bubbles had initial radii of approximately  $R_i = 1.65$  mm. A waveform in Fig. 11a corresponds to a relatively small pressure step  $\Delta p = 280$  kPa. In this case the bubble is excited to a weakly nonlinear oscillation, and the radiated wave, which is superimposed upon the pressure step  $\Delta p$ , resembles a distorted harmonic wave. Due to a weak pressure signal the influence of noise in the preamplifier and in the A/D converter is rather strong.

In Fig. 11b a pressure wave emitted by a more intensively oscillating bubble is shown. In this case the pressure step is  $\Delta p = 480$  kPa. The increasingly nonlinear bubble wall motion is accompanied by a corresponding increasingly nonlinear radiated waveform. Finally, Fig. 11c presents the pressure wave emitted by a rather violently oscillating bubble ( $\Delta p = 990$  kPa). Note that when increasing the pressure step  $\Delta p$  the peak pressure in the radiated wave grows significantly and also the bubble oscillation period (distance between two consecutive peaks in the wave) decreases considerably. The recorded waveforms are of good quality and allow for a detailed evaluation and comparison with theoretical results.

#### 4. Conclusion

The shock tube proved to be a very useful tool for bubble dynamics studies. By varying the pressure  $p_4$  (and thus the pressure step  $\Delta p$ ) the bubble could be excited to oscillate with different intensities which made it possible to study its behaviour under different conditions. The bubble shape could be monitored by a simple photographic setup. To monitor the pressure wave radiated by an oscillating bubble a needle hydrophone had to be used, which had to be positioned very close to the bubble. Only then good quality pressure records could be obtained. Several interesting side-effects were observed, the nature of which is not quite clear yet.

The experimental part of this research was carried out during the author's stay at the Shock Wave Laboratory of the Technical University in Aachen. The author wishes to thank Prof. A. E. Beylich for enabling him to do this work and for many helpful discussions, and H. Kleine for taking all the photographs. During this research the author was a recipient of Heinrich Hertz Stiftung, which is gratefully acknowledged.

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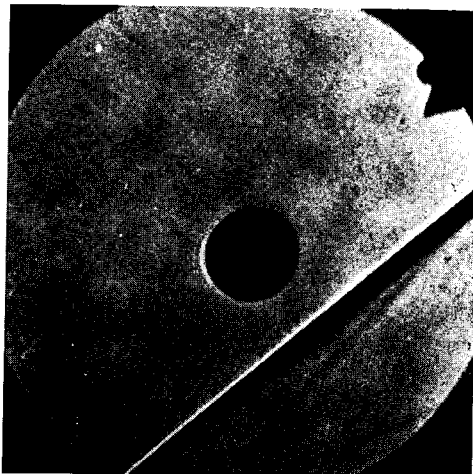


Fig. 9. Schlieren photograph of a precursor travelling across an  $N_2$  bubble in glycerine ( $\Delta p = 1.06$  MPa).

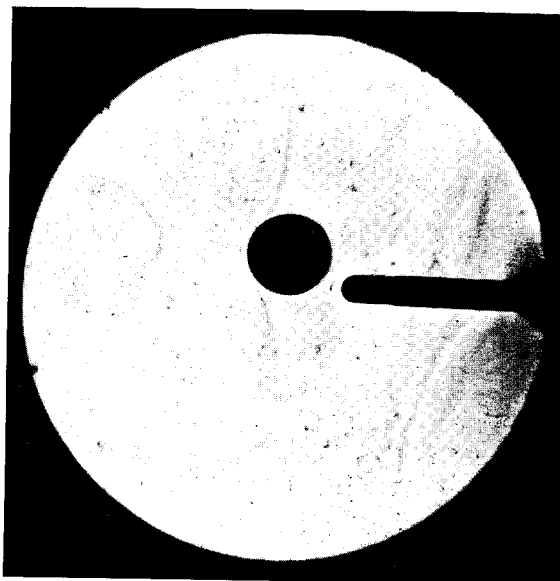


Fig. 10. Photograph of an  $N_2$  bubble oscillating in glycerine in the vicinity of the needle hydrophone ( $p_4 = 1.22$  MPa).