ACUSTICA
Vol. 78 (1993)

Experiments with Oscillations of Non-spherical Gas Bubbles Oscillating in a Liquid-shock-tube

K. Vokurka
Department of Research and Development, LIAZ a.s., Jablonec n.N., Czech Republic

Experiments with Non-spherical Gas Bubbles Oscillating in a Liquid-shock-tube

Summary

Non-linear oscillations of non-spherical gas bubbles in a liquid are studied experimentally. Bubbles are excited into oscillation using a liquid-shock-tube. Bubble shapes are monitored by a rotating mirror camera. Pressure waves radiated by oscillating non-spherical bubbles are picked up by a needle hydrophone. The paper concentrates on the analysis of pressure records and associated acoustic energies. Experimental data are compared with theoretical predictions for spherical bubbles. It is found that even highly non-spherical bubbles radiate intensive pressure waves of almost the same form and strength as predicted by the theory for spherical bubbles. Abrupt changes in the length of the third oscillation period occur when increasing the driving pressure step strength. Similarly, anomalies in the measured peak and trough pressures are found. This report is an extension of a previous paper, which was devoted to non-linear oscillations of spherical gas bubbles.

Experimente mit nicht-sphärischen schwingenden Gasblasen in einem Flüssigkeits-Stoßrohr

Zusammenfassung

Es werden die nichtlinearen Schwingungen von nicht-sphärischen Gasblasen in einer Flüssigkeit experimental untersucht. Die Blasen werden mit Hilfe eines Flüssigkeitsstoßrohrs zu Schwingungen angeregt, und ihre Form wird mit einer Drehspiegelkamera beobachtet. Die won den schwingenden, nicht-spärischen Blasen abgestrahlten Druckwellen werden mit einem Nadelhydrophon aufgenommen. Die Arbeit konzentriert sich auf die Untersuchung der Druckmessungen und der damit verbundenen Energien. Die experimentellen Daten werden mit theoretischen Vorhersagen für sphärische Blasen verglichen. Es zeigt sich, daß sogar hochgradig nicht-sphärische Blasen intensive Druckwellen fast von der gleichen Form und Stärke abstrahlen, wie sie von der für kugelförmige Blasen gültigen Theorie vorhergesagt werden. Abrupte Änderungen in der Dauer der dritten Schwingungsperiode treten auf, wenn der antreibende Drucksprung vergrößert wird. Des weiteren werden Anomalien in den gemessenen Maximal- und Minimaldrükken gefunden. – Diese Arbeit ist eine Erweiterung einer früheren Veröffentlichung über nichtlineare Schwingungen sphärischer Gasblasen.

Etude expérimentale des oscillations de bulles gazeuses non sphériques dans un tube à choc empli de liquide

Sommaire

Cet article est consacré à l'étude expérimentale des oscillations non linéaires de bulles de gaz non sphériques dans un liquide. La technique consiste à produire une onde de choc qui engendre les oscillations des bulles, à observer la déformation des bulles à l'aide d'une caméra à miroir tournant, puis à enregistrer à l'aide d'un microphone à aiguille les ondes de pression rayonnées par les bulles non sphériques en mouvement. L'étude est concentrée sur l'analyse des enregistrements de pression et de l'énergie acoustique associée, et l'on compare les données expérimentales aux résultats théoriques valables pour les bulles sphériques. On constate que des bulles même fortement non sphériques rayonnent des ondes de pression dont la forme et l'amplitude sont analogues à celles que prévoit la théorie applicable aux bulles sphériques. Des changements abrupts de la longueur de la troisième période d'oscillation apparaissent lorsque l'on augmente l'intensité de l'échelon de pression d'excitation. On observe également des anomalies dans la répartition des pics et des crevasses de pressions mesurées. Ce rapport fait suite à un article antérieur, qui était consacré à l'étude des oscillations non linéaires de bulles de gaz sphériques.

1. Introduction

Liquid-shock-tubes have proved to be a useful tool in studies of bubble dynamics [1–4]. An obvious advantage of this method is that a pressure step generated in a shock-tube, can excite bubbles into free oscillations in a well-defined manner. However, there is a serious limitation of this method: when a spherical bubble interacts with the pressure step, its shape is usually deformed. As spherical bubbles play a special role in today's research (i.e. only in this case are the existing mathematical models simple enough to allow reasonably fast computations), the shock tube studies are usually limited to the time interval during which bubble sphericity is retained [4].

Received 5 November 1992,
accepted 11 January 1993.

K. Vokurka, Department of Research and Development, LIAZ a.s., Belgická 400, CS-46605 Jablonec n.N., Czech Republic.

However, long term observations of bubbles that have been excited into oscillation by a shock tube can be used to obtain valuable experimental data on phenomena associated with non-spherical bubble shapes. Smulders and van Leeuwen [1] studied bubble shape oscillation using high-speed photography and revealed, among other things, a good reproducibility of complicated bubble shapes. In this paper we shall examine the pressure waves radiated during non-linear oscillation of non-spherical bubbles, and the acoustical energies associated with these waves. The results presented here are a supplement to the earlier paper [4]. However, whereas in Ref. [4] the main interest concentrated on spherical bubbles, here non-sphericity is stressed.

One of the earliest studies of the pressure waves radiated by the oscillation of non-spherical bubbles was conducted by Strasberg [5]. Strasberg found that appreciable sound is radiated only when the bubble is in volume pulsation and, according to him, it does not seem that shape oscillations would ever result in significant sound pressures. Recently an interest in acoustic radiation of non-spherical bubbles was revived by the theoretical work of Longuet-Higgins [6], who showed that in the case of the shape oscillations, the pressure field becomes large when a doubled frequency of some spherical harmonic approaches the frequency of the fundamental radial mode (volume pulsations). According to Longuet-Higgins, this can be regarded as a resonance between the driving spherical harmonic and the radial mode of oscillation. The experimental data presented here are analyzed in Section 4 from the point of view of Strasberg's [5] results. However, no attempt is made to verify the Longuet-Higgins [6] theory.

2. Experimental arrangement

The experimental arrangement used here to study the oscillations of non-spherical gas bubbles is the same as that described in Ref. [4]. Therefore only a brief summary is given here. The vertical shock tube used in the experiments consisted of three sections. The high-pressure section was filled with nitrogen at a pressure p_4. The low-pressure section contained air at atmospheric pressure $p_1 = 0.1$ MPa. The lowest section of the tube was filled with 85% diluted glycerine. The high- and low-pressure sections were separated by a membrane. The heating wires were used to tear up the pre-stressed membrane at a precisely defined moment.

The experimental nitrogen bubbles were generated at the orifice of a small L-shaped tube submerged in glycerine. The bubbles rose with a velocity of about 0.06 m s^{-1}. A light gate was used to synchronize bubble ocurrence in an observation section with the discharge of a condenser battery across the heating wires, and the following initiation of a shock wave in the air. The shock wave was transmitted into glycerine as a pressure step having a rise time of about $\Delta t = 20\,\mu\text{s}$. The pressure step strength, Δp, varied according to p_4 and ranged from 0 to 1.1 MPa. The constant part behind the leading edge of the pressure step lasted for approximately $\Delta T = 750\,\mu\text{s}$. This is the maximum time interval for observation of the phenomena studied.

The pressure field, p, in the liquid was monitored by a needle hydrophone, the sensitive area of which was usually set at a distance $r = 3$ mm from the bubble centre. The bubble wall motion was observed by a rotating mirror camera with framing rates up to $250\,000 \text{ s}^{-1}$. Further details regarding the experimental arrangement used can be found in Refs. [4, 7].

3. Results

It was observed that when no pressure step propagates along the shock tube, the nitrogen bubbles of initial radii $R_i < 2$ mm rising in glycerine always preserve their spherical shape. However, the interaction of a rising bubble with a pressure step produces a bubble oscillation. For all pressure step strengths, Δp, used in the present experiments, the bubbles remained spherical during their first compressions. This was not always true for later times. For approximately $\Delta p > 0.4$ MPa, bubble shape distortions set in and these deformations could be detected first when the bubbles were compressed to their minimum volumes. The deformations were larger for stronger pressure steps, and also grew in successive bubble oscillation periods. However, during the first bubble expansions, the bubbles usually showed a tendency to recover their sphericity.

For stronger pressure steps and/or later oscillation periods the bubbles acquired very complicated shapes but, as was shown in Ref. [1], these oscillation modes are quite reproducible, providing the other conditions are kept the same (Δp, R_i, etc.). An example of oscillating bubble photographs obtained with a rotating mirror camera is given in Fig. 1. In this particular case the bubble was excited into oscillation by a pressure step $\Delta p = 1.06$ MPa. The framing rate was $250\,000 \text{ s}^{-1}$, however, only selected frames are shown. The selection was done in such a way that the frames in the first column display the bubble at its successive maximum volumes and in the third column at successive minimum volumes. Thus, the first two oscillation periods are encompassed. In Fig. 1 a precursor can be seen in the first frame, and it can also be seen that the bubble

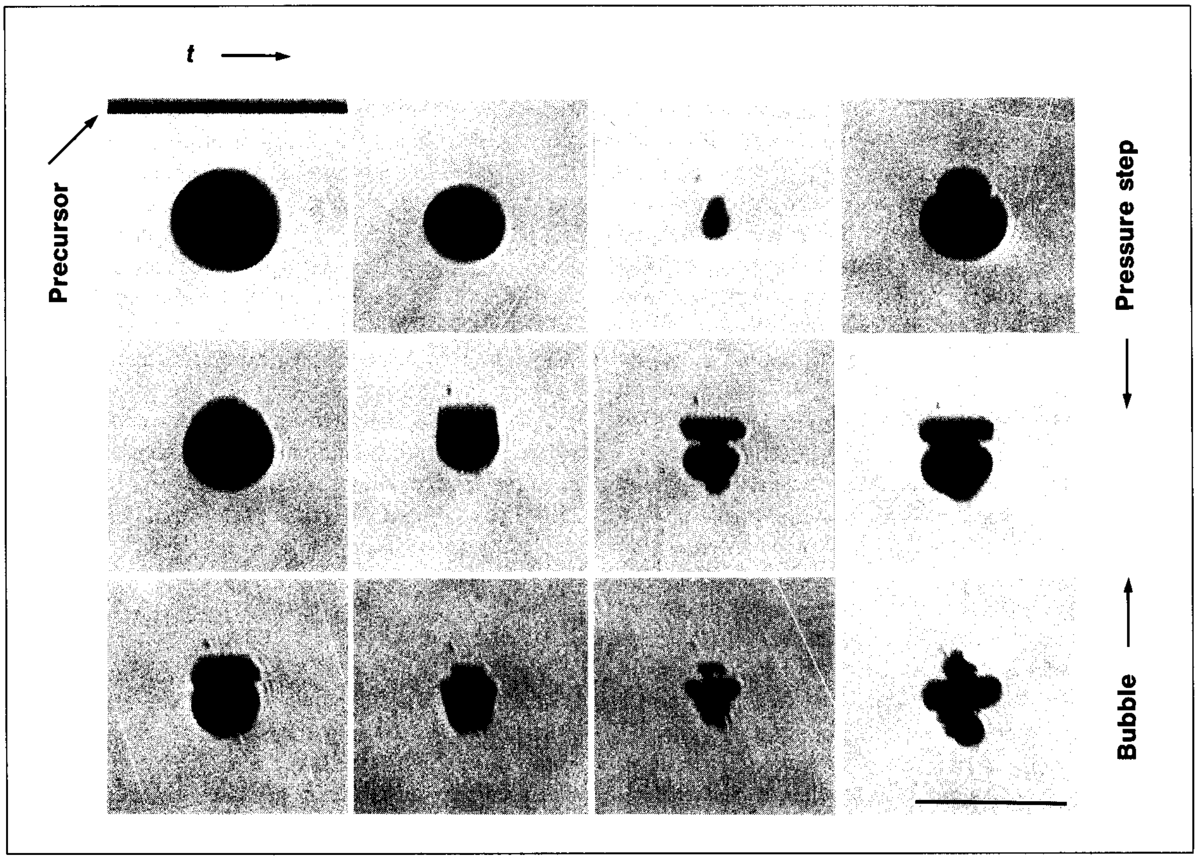

Fig. 1. Example of an oscillating nitrogen bubble in glycerine ($R_i = 1.67$ mm, $\Delta p = 1.06$ MPa). The frames were taken at times t of 0, 52, 76, 108, 144, 172, 200, 220, 244, 264, 276 and 308 μs. Bar 5 mm.

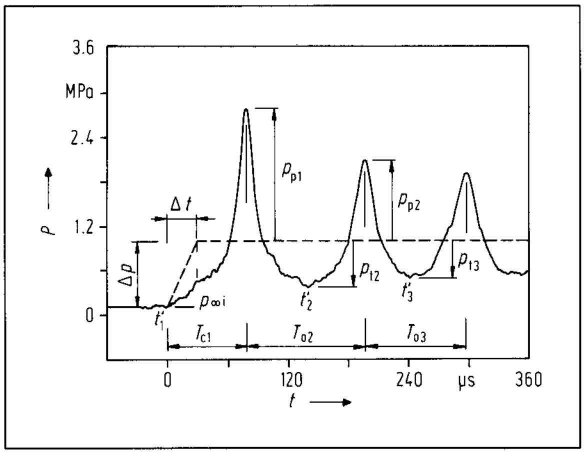

Fig. 2. Example of the pressure record p in glycerine with an oscillating nitrogen bubble. The pressure p was measured at a distance $r = 3$ mm from the bubble's centre, the estimated bubble initial radius was $R_i = 1.65$ mm, the initial ambient pressure $p_{\infty i} = 0.1$ MPa, and the driving pressure step $\Delta p = 0.83$ MPa.

shape deformations are symmetrical with respect to the direction of the pressure step propagation (or, which is the same, to the direction of the bubble translation).

An example of the pressure signal, p, taken with the hydrophone is shown in Fig. 2. Let us remember that in this case the pressure field, p, is formed by the superposition of the variable ambient pressure (the pressure step), p_∞, and the acoustic wave, p_a, radiated by the oscillating bubble. A surprising fact of note in Fig. 2 is that although the bubble shape is highly non-spherical for later times (cf. Fig. 1), the bubble radiates intensive pressure pulses, the amplitudes of which seem to be little influenced by the distorted shapes.

From the pressure waves recorded in different experiments, a number of quantities could be easily determined (for definition of these quantities see Fig. 2), these being the times of the second and third oscillation periods T_{02} and T_{03}, the first and second peak pressures p_{p1} and p_{p2}, the second and third through pressures p_{t2} and p_{t3}, and the acoustical energies associated with the first and second bubble pulses ΔE_{a1} and ΔE_{a2}, respectively. Whereas the quantities T_{02}, T_{03}, p_{p1}, p_{p2}, p_{t2} and p_{t3} could be read out directly from the pressure records, the energies ΔE_{a1} and ΔE_{a2} were calculated using the formula

$$\Delta E_a = 4\pi r^2 \frac{1}{\varrho_\infty c_\infty} \int_{t_1}^{t_2} p_a^2 \, dt . \qquad (1)$$

Here r is the distance from the bubble's centre to the point at which p is being measured, ϱ_∞ is the liquid density, c_∞ the velocity of sound in the liquid, t_1 and t_2 are identified with the time instants of the successive trough pressure occurrences, and $p_a = p - p_\infty$.

The variation of these quantities and of their ratios with the pressure step strength Δp are displayed in Figs. 3 to 6. In Figs. 3 to 6, theoretical curves are shown together with experimental points. The theoretical data were obtained under the assumption of a spherical bubble shape using the bubble model given in Ref. [4].

A number of interesting features can be seen in Figs. 3 to 6. For example, the experimental data for T_{02} show close agreement with the theoretical variation, and this agreement is even better for stronger Δp, when the bubbles have evidently lost their sphericity. On the other hand, for weaker pressure steps $\Delta p < 0.3$ MPa, when the bubbles are spherical, the differences between the theoretical and experimental data are the largest. This is not true as far as T_{03} is concerned. Here, for weaker pressure steps the experimental points do lie in the vicinity of the theoretical curve. However, in this case an interesting jumping phenomenon can be seen. If we denote $\Delta p_j = 0.52$ MPa as the pressure step strength for which the jump occurs, then for $\Delta p < \Delta p_j$ the experimental points lie above the theoretical curve and for $\Delta p > \Delta p_j$ they lie under it. When one tries to approach the jumping pressure step strength Δp_j either from the left or from the right the variance of the experimental values of T_{03} always increases. This behaviour can be seen perhaps even better from the plot of the ratio T_{03}/T_{02} given in Fig. 3c. Here for $\Delta p < \Delta p_j$, $T_{03} > T_{02}$; and for $\Delta p > \Delta p_j$, $T_{03} < T_{02}$.

Variations of p_{p1} and p_{p2} with Δp are shown in Fig. 4. In this case the experimental points of both p_{p1} and p_{p2} lie under the theoretical curve. Again it is the ratio of p_{p2}/p_{p1} which reveals that for a certain range of pressure steps there is a tendency for the second peak pressure to be higher than the first one, i.e. $p_{p2} > p_{p1}$. This contradicts what one would intuitively expect for damped bubble oscillations. It should be also noted that the experimental data displayed in Fig. 4a correspond to a spherical bubble shape (as was mentioned above, the bubbles retained a spherical shape during the first compression for all values of Δp). On the other hand, the experimental data displayed in Fig. 4b for $\Delta p > 0.4$ MPa correspond to the non-spherical bubble shapes. Surprisingly, the bubble shape deformations have little effect on the radiated peak pressures (cf. Fig. 1, where for $t = 200$ µs the highly deformed bubble shape at the second minimum

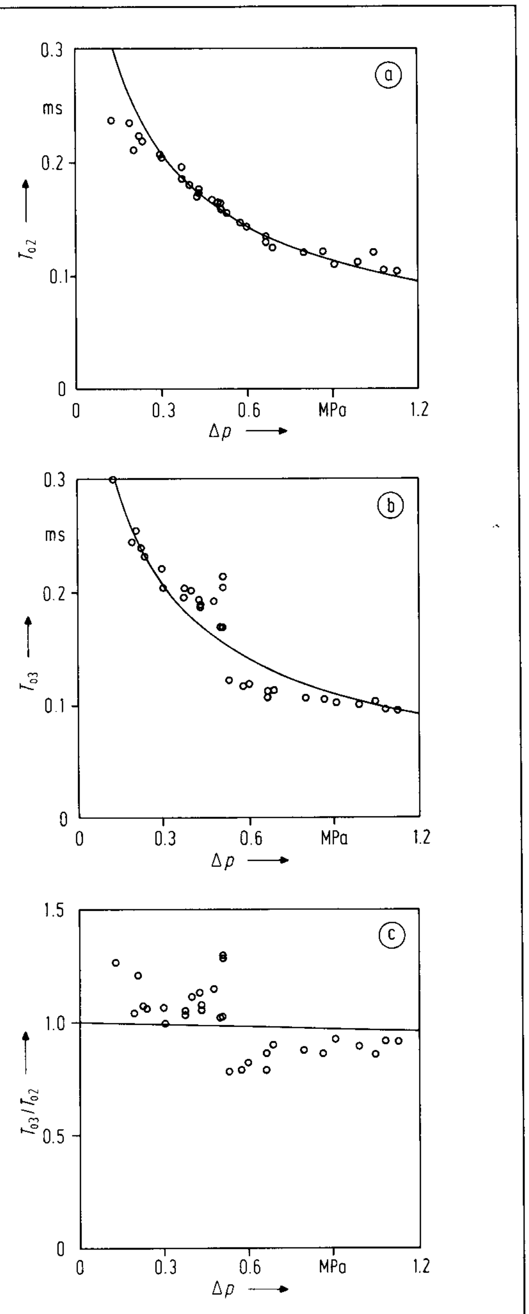

Fig. 3. Variation of the oscillation time data with the pressure step Δp; (o) experiment, (——) theory. a) Second oscillation time T_{02}, b) third oscillation time T_{03}, c) ratio T_{03}/T_{02}

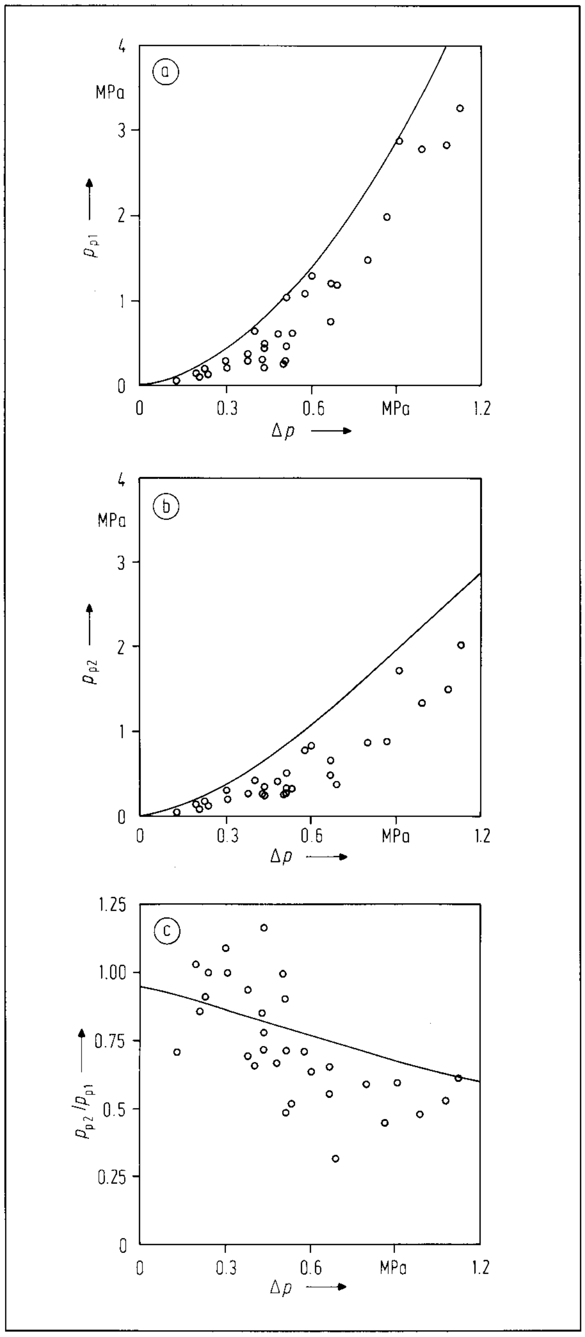

Fig. 4. Variation of the peak pressure data in the radiated wave with the pressure step Δp; (o) experiment, (——) theory. a) First peak pressure p_{p1}, b) second peak pressure p_{p2}, c) ratio p_{p2}/p_{p1}.

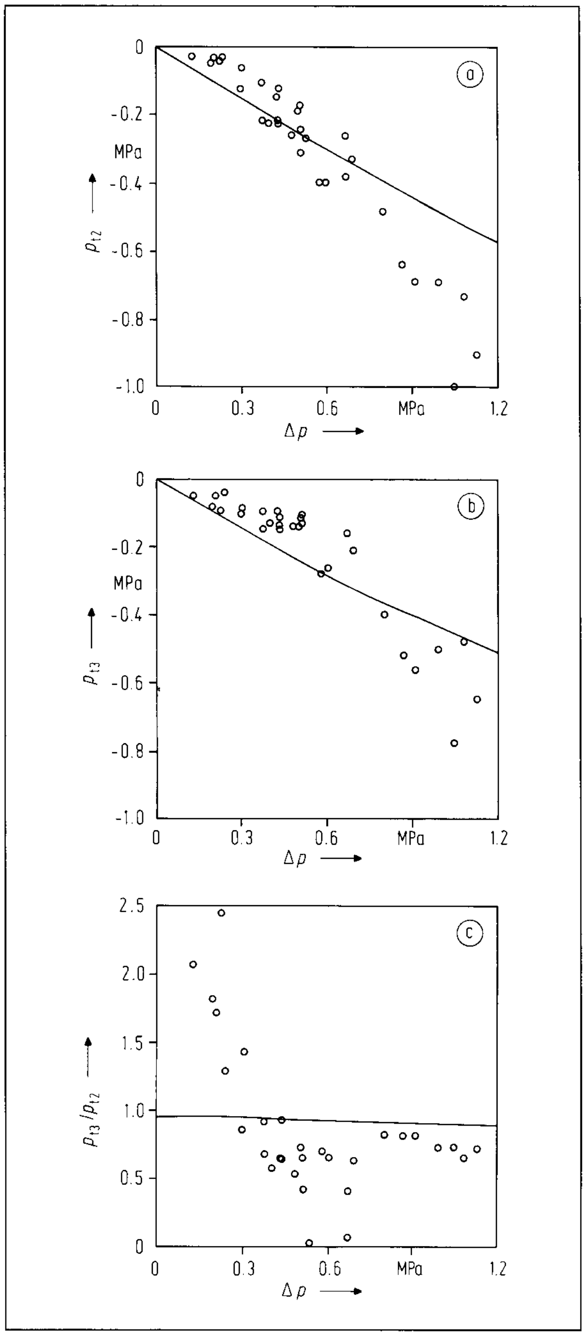

Fig. 5. Variation of the trough pressure data in the radiated wave with the pressure step Δp; (o) experiment, (——) theory. a) Second trough pressure p_{t2}, b) third trough pressure p_{t3}, c) ratio p_{t3}/p_{t2}.

volume is shown; it is exactly at this time that p_{p2} was radiated).

When observing Fig. 5 one can see behaviour similar to that in Fig. 4. Again, the distributions of experimental points both in Fig. 5a and 5b show similar patterns though the bubble shape was much more deformed at the times when p_{t3} was radiated. One can see in Fig. 5a and 5b that for weaker pressure steps, the measured trough pressures are less negative, and for stronger Δp more negative, than predicted by the theory. Further details are discovered from Fig. 5c, where the ratio p_{t3}/p_{t2} is displayed. For weaker steps

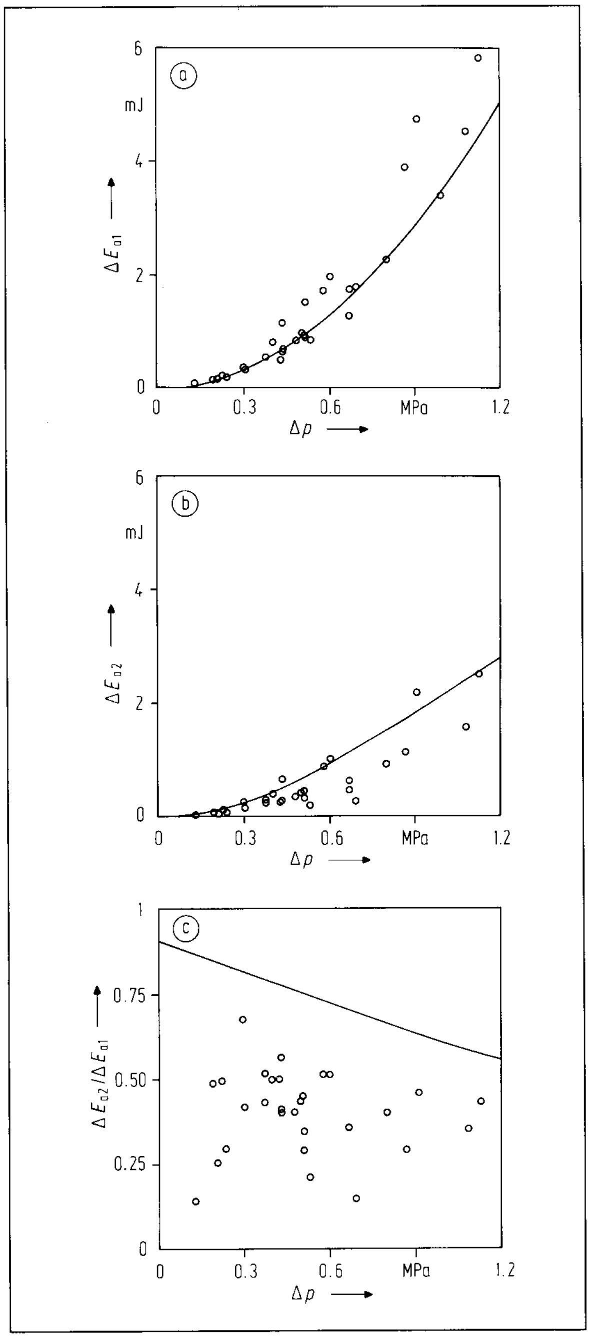

Fig. 6. Variation of the acoustic energy data with the pressure step Δp; (o) experiment, (——) theory. a) Acoustic energy in the first bubble pulse ΔE_{a1}, b) acoustic energy in the second bubble pulse ΔE_{a2}, c) ratio $\Delta E_{a2}/\Delta E_{a1}$.

(roughly for $\Delta p < 0.3$ MPa), $p_{t3} > p_{t2}$, and for stronger ones (roughly for $\Delta p > 0.3$ MPa) $p_{t2} > p_{t3}$. As in the case of p_{p1} and p_{p2}, for weaker steps the behaviour of the bubbles contradicts what one would expect.

Finally in Fig. 6a one can see that real bubbles radiate the acoustic energy more intensively in the first bubble pulse than predicted by the theory. On the other hand, as can be seen in Fig. 6b, the acoustic energy carried away by the second bubble pulse is smaller than the theoretical one. Even now, despite the highly deformed bubble shape, the experimental radiated energy is almost comparable with the theoretical energy computed for spherical bubbles. The ratio $\Delta E_{a2}/\Delta E_{a1}$ shown in Fig. 6c confirms what could be seen in Figs. 6a and 6b, i.e. that for any pressure step Δp, $\Delta E_{a1} > \Delta E_{a2}$.

4. Discussion

The experimental data presented in the preceding section indicate that apart from some interesting deviations mentioned here and in Ref. [4], the oscillating non-spherical bubbles radiate pressure waves, which are basically the same as those predicted by the theory for radially pulsating spherical bubbles. A possible explanation for this suppression of the influence of the bubble shape deformation is as follows. During the interaction with the driving pressure step, the bubble is excited to perform both the basic radial pulsations and the higher mode shape oscillations. However, as was shown by Strasberg [5], the shape oscillations have much lower frequencies than the radial pulsations and they radiate pressure components which diminish rapidly with distance. Owing to their low frequencies, the shape oscillation pressure components should manifest themselves in the measured time signals as slowly varying trends, which could be observed only on a larger time scale (e.g., in Fig. 2, the time of the radial oscillations is ≈ 120 μs, but the time of the second mode shape oscillation is 16.53 ms, of the third mode shape oscillation 9.05 ms, etc.; see Ref. [5], for the respective formulae and Ref. [4] for the physical constants). Besides, the pressure due to the n-th mode shape oscillation varies inversely with the $(n+1)$th power of the distance r [5], and this also helps to explain why at $r = 3$ mm only the pressure component due to the radial pulsations is significant.

One can thus see that the radiation mechanism acts as a filter, which passes the components due to the radial pulsations, and attenuates the components due to the shape oscillations. Hence the pressure wave conveys information concerning the zero mode first of all, which in photographs of bubbles could otherwise be hidden in the higher mode shape oscillations.

This observation is in good agreement with results obtained in experiments on low-intensity (linear) bubble oscillations [5, 8–11]. There it was observed that despite pronounced shape oscillations, the radiated acoustic waves had the form of decaying sinusoids with frequencies corresponding to the linear radial pulsations of the spherical bubbles. The results presented in this paper can be then viewed as an extension of the works [5, 8–11] into the region of higher bubble oscillation intensities, where the bubble behaviour already has a non-linear character, and hence the radiated waves are far from simple sinusoids (see, e.g., Fig. 2).

The previously mentioned property of the radiated waves made it possible to determine in Ref. [12], using the data given in Refs. [5, 8], the amplitudes of the linear radial bubble pulsations. The computed amplitudes were very low and, because of the pronounced low-frequency shape oscillations of the bubbles, the radial pulsations could hardly be observed directly in high-speed photographs, such as those given in Fig. 3 of Ref. [5]. It is only the pressure signal which made it possible to determine their amplitudes and frequencies.

For further experimental work, a criterion of what distance r is close to the bubble and what is not close is needed. Strasberg [5] suggested a wavelength of the radiated sound for this purpose. In the case of a linearly oscillating bubble in glycerine (initial radius $R_i = 1.65$ mm, polytropic exponent $\gamma = 1.4$, ambient pressure $p_\infty = 100$ kPa, and liquid density $\varrho_\infty = 1220$ kg m^{-3}) the frequency of pulsations is $f_0 = 1791$ Hz (see, e.g., Ref. [5] for the formula), and hence the respective wavelength is $\lambda = 1.07$ m (the speed of sound in glycerine is $c_\infty = 1920$ m s^{-1}). However, the data presented here suggest that the respective distance (the boundary between "near" and "far") will most probably be much smaller. Here, at a distance of $r = 3$ mm no significant pressure component due to the shape oscillation was found.

Unfortunately, the conclusions presented above are more or less qualitative in their nature. To be able to discuss them in quantitative terms, one would need a method of spectral analysis enabling resolution of the complicated bubble shapes, such as those shown in Fig. 1, into particular spherical harmonics. In this respect the measurement of the pressure signal can be used to determine the amplitude and frequency of the zero mode oscillation.

To support the conclusions presented above, a knowledge of how the radiated pressure waveform varies with both distance and direction would be helpful. Unfortunately, the usable values of r were limited in the experiments to between 3 and 5 mm. The upper bound on r was given by an erratic "damping", mentioned in Ref. [7]. This "damping" hindered recording of clean waveforms for larger distances r (the same phenomena made it difficult to obtain good low-intensity pressure records). The lower bound on r was given by the possible influence of the needle hydrophone on the bubble behaviour [7]. Similarly, the recording of the pressure waveforms in different directions was also not possible with the present experimental arrangement.

As far as the Longuet-Higgin's theory [6], mentioned in the Introduction section, is concerned, no attempt was made here to detect a possible transfer of energy between different modes. The reason was that much longer intervals of observation than were used here would be needed for this purpose. Besides, in this author's opinion, only a minor role of such an energy transfer should be expected under the circumstances of the intensive non-linear radial pulsations studied here.

However, the results of the experiments throw a new light on another earlier speculation. It has been suggested [12] that the bubble shape distortions could be a cause of the observed increased energy losses of oscillating bubbles. The analysis of the radiated pressure waves carried out in Section 3 showed, however, that this need not always be the case. Hence, it seems that the cause of the mysterious energy dissipation must be sought elsewhere.

The observed behaviour of the third oscillation period T_{03} is also very interesting. One would expect that because of the energy dissipation we should always find $T_{02} < T_{03}$. However, as follows from Fig. 3c, this is true only for higher intensity oscillations; and even for a higher intensity the ratio T_{03}/T_{02} does not decrease with an increase in the pressure step strength Δp. This behaviour evidently corresponds to that of the ratio R_{M2}/R_i (R_{M2} is the second maximum radius) as discussed in Ref. [4], which also does not conform to the theoretical prediction for "ordinary" bubbles. (Note that both these ratios are used as measures of bubble oscillation damping.)

Last, the variance of the measured data deserves a short comment. All the data presented in Figs. 3 to 6 were determined from recorded pressure waves. At the same time the bubble sizes and positions were assumed fixed. Though the generated bubbles were very reproducible, their actual size, R_i, could vary slightly from one experiment to another. Also the distance, r, between the hydrophone's sensitive area and the bubble centre could vary slightly in different experiments. These variations, which had the form of random fluctuations (not of a systematic error), naturally influenced the values of the measured and computed quantities. To improve the data quality, one obviously has to record the pressure waves concurrently with photographing the bubbles, and thus to obtain for every pressure record the actual bubble size and position. Of course, further improvements are needed in determining the time variable ambient pressure p_∞ more precisely (this question is discussed in greater detail in Ref. [7]).

5. Conclusion

Measurement of the pressure waves radiated during the non-linear oscillation of non-spherical bubbles has revealed a number of interesting facts:

(1) In the recorded signals, only the pressure components due to the radial pulsation are significant. This was verified even for distances much closer to the bubble than suggested by Strasberg [5].
(2) When increasing the intensity of the oscillation, the pattern of bubble behaviour abruptly changes. For low intensity oscillation $T_{02} < T_{03}$, for higher intensity $T_{02} > T_{03}$. The transition between the two regimes is discontinuous.
(3) For certain values of the driving pressure step Δp, $p_{p2} > p_{p1}$ and $p_{t3} > p_{t2}$. This contradicts what one would expect for ordinary bubbles.

For further research a number of suggestions can be formulated:

(a) To verify some of the conclusions made above it is necessary to analyze more bubble oscillation periods, and to measure the pressure signal at various distances and in different directions.
(b) A method enabling resolution of the deformed bubble shapes into spherical harmonics is needed.
(c) To increase the precision of the measured data, simultaneous recording of the pressure waves and photographing of the bubbles is necessary.

Acknowledgement

The results presented in this report were obtained during the author's stay at the Shock Wave Laboratory of the Technical University in Aachen. The author wishes to thank Professor A. E. Beylich for enabling him to do this work and H. Kleine for taking the photographs. During this research the author was a recipient of a grant awarded by the Heinrich Hertz Foundation, which is gratefully acknowledged.

References

[1] Smulders, P. T., van Leeuwen, H. J. W., Experimental results on the behaviour of a translating gas bubble in water due to a pressure step. In: Finite-amplitude wave effects in fluids, Bjørnø, L., ed., IPC Science and Technology Press, Guildford 1974, pp. 227–233.
[2] Fujikawa, S., Akamatsu, T., Experimental investigations of cavitation bubble collapse by a water shock tube. Bull. JSME **21** [1978], 223–230.
[3] Gülhan, A., Beylich, A. E., Untersuchungen zur Dynamik von Gasblasen. Acustica **63** [1987], 276–282
[4] Vokurka, K., Beylich, A. E., Kleine, H., Experimental study of gas bubble oscillations using a shock tube. Acustica **75** [1992], 268–275.
[5] Strasberg, M., Gas bubbles as sources of sound in liquids. J. Acoust. Soc. Amer. **28** [1956], 20–26.
[6] Longuet-Higgins, M. S., Monopole emission of sound by asymmetric bubble oscillations. Part 1. Normal modes. Part 2. An initial-value problem. J. Fluid Mech. **201** [1989], 525–541, 543–565.
[7] Vokurka, K., The use of a shock tube in bubble dynamics studies. Czech. J. Phys. **42** [1992], 291–302, 344a.
[8] Leighton, T. G., Walton, A. J., An experimental study of the sound emitted from gas bubbles in a liquid. Eur. J. Phys. **8** [1987], 98–104.
[9] Leighton, T. G., Fagan, K. J., Field, J. E., Acoustic and photographic studies of injected bubbles. Eur. J. Phys. **12** [1991], 77–85.
[10] Pumphrey, H. C., Crum, L. A., Free oscillations of near-surface bubbles as a source of the underwater noise of rain. J. Acoust. Soc. Amer. **87** [1990], 142–148.
[11] Pumphrey, H. C., Ffowcs Williams, J. E., Bubbles as sources of ambient noise. IEEE J. Oceanic Engng. **15** [1990], 268–274.
[12] Vokurka, K., Amplitudes of free bubble oscillations in liquids. J. Sound Vib. **141** [1990], 259–275.