SECONDARY CAVITATION WAVES IN A POLYDISPERSE BUBBLE CLUSTER

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ABSTRACT

The work is devoted to theoretical and experimental study of processes of wave interaction in cavitational bubble cluster. A polydisperse bubble cluster is modeling as a two-fraction bubble cluster (micro-bubbles and macro-bubbles). It is shown that they differ with opposite phases of oscillation and time of a collapse. It is shown, that micro-bubbles, which accumulate energy in an initial bipolar acoustic wave, collapse in a field of internal positive pressure in the cluster. Secondary wave of compression generated by inertial expansion of macro-bubbles is determined by the numerical modeling and is experimentally registered. For the pulse compression in a cluster a reduction of a period and strengthening of the collapse are shown for micro-bubbles.

INTRODUCTION

The numerical modeling of a flow behind an acoustic bipolar wave in water with gas bubbles is carried out. As is known, the shock wave in water after reflection from a free surface generates a rarefaction wave. The presence of gas bubbles essentially complicates a flow field. Behind a falling wave the bubbles begin to shrink, their size decreases, and in environment a local non-uniformity with the increased pressure is forming. In the reflected rarefaction wave, the energy at the non-uniformity is quickly liberated. There are compression waves, which generate a secondary shock followed the rarefaction wave. The conditions of a secondary wave occurrence, their intensity, interaction with the initial impulse are the objects of the present research.

The results of experimental and computational research are presented. The dynamics of gaseous bubbles generation and interactions in a liquid is investigated when bipolar impulse passes through the medium and the interval between rarefaction and compression waves is a variable. The falling shock wave compresses a bubble cluster. When subsequent rarefaction wave passes, the bubbles generate a secondary shock wave, which may be quite strong under certain conditions. The cavitation processes in a liquid has been generated experimentally with the help of electromagnetic generator of convergent acoustic pulse having a form of hollow sphere segment. The modelling has been performed within the frame of two-dimensional axisymmetric non-stationary approach on the base of conservation laws for the model of ideal compressible liquid. The thermodynamic flow field has been computed both in the liquid and in the bubble.

It was found out that the smaller bubble collapses in the cavitation track of the bigger one and the amplitude of the secondary shock may exceed one of the initial wave.

EXPERIMENTAL RESULTS

Hydrodynamic processes in a field of spherically focusing shock wave were investigated by a high-speed photo-recording and a pressure field measurement in a distilled water. Cavitation processes in a focal area were recorded by a shadow method using a high-speed photo recorder ÑÔÐ-1ì in a frame mode. An electromagnetic shock wave generator [1] with a transducer shaped as a sphere segment with a focal distance of 170 mm, an aperture of 220 mm was used. The transducer was installed on the bottom of a bath measured 320 õ 320 õ 760 mm. A pressure field was controlled with a hydrophone having a time resolution of 0.05 us and a space resolution of 0.7 mm. The shock wave had a bipolar profile with compression wave and a strong rarefaction wave of 2 us duration. A pressure on the transducer was varied from 0.2 to 0.8 MPa.

A comparison of pressure profiles and images of cavitation has revealed a pressure threshold for cavitation of p_M = 0.4 MPa. The photo-recording (Fig. 1) was performed for a shock wave with p_M = 0.65 MPa. The cavitation cluster is shaped as an ellipsoid having a center about 10 mm below the geometrical focus of the transducer. Hence, it can help to distinguish effects of the positive and the negative pulse.

To explain the experimental results we refer to a scheme in Fig. 2 where key phenomenon are shown. It illustrates a wave geometry near the focus at three moments of time numbered from (I) to (III). The first stage corresponds to an initial convergent compression pulse (1) and diffracted compression pulse (3) (solid lines) before the focus. Due to diffraction on the edge of the transducer the initial compression pulse produces an edge rarefaction wave (2) (dashed lines). Hence, the rarefaction wave is shaped as a tore segment focusing on the axis of symmetry (7). The negative pressure results in cavitation - growing bubbles (5) in vicinity of a point (K). Due to acoustic scattering each bubble is a center of spherical diverging acoustic wave (6). Pressure in the pulse is given in [2] by equation

$$p = \rho\ / (4\pi L)\ d^2V/dt^2 = \rho\ R\ (R(d^2R/dt^2)+2\ (dR/dt)^2)\ /\ L \qquad (1)$$

where ρ is a density of liquid, L is a distance from a center of a bubble to a point of observation, V is a volume of the bubble. Hence, the cavitational bubbles being expanding in crossed rarefaction pulses, disturb the pressure by positive pulse founded in experiment [4] and described theoretically in [5]. In the figure 2 at the moment (I) the source of the compression wave is a point (K). The point (K) moves along the axis with a supersonic speed

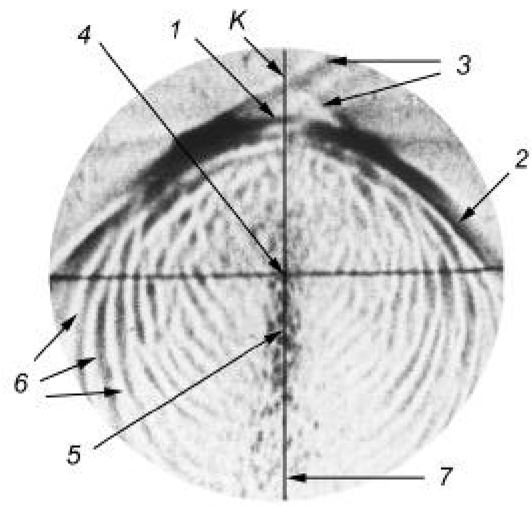
$$u = c\ /\ \cos\ (A) \qquad (2)$$

where c is a sound speed of 1.5 mm/us and A is a current angle between a normal to wave front and the axis Z at the point (K). Measured for the cavitation zone the angle A ranges from 40 to 45 degrees. As a result, the rarefaction pulse is transformed into a compression pulse because of cavitation and an interference of the secondary waves from each bubble. Thus, the back front of the rarefaction pulse is the same that a front of the compression pulse from cavitation. It is followed from a comparison of pressure profiles and images taken for p_M was both below and above the threshold that the waves (6) are directly connected with cavitation. In other words, cavitation non-linearity is a necessary condition for the transformation. The detailed bubble dynamics and pressure disturbances should be numerically calculated.

On the next stage II the compression pulse reaches the geometrical focus (4) where it has a maximum pressure peak. Then it becomes divergent and on the last shown stage III the wave picture corresponds to the experimental one. Then one can observe a bubble pulsations and emitted shock waves at the bubble collapse. Periods of the first and the second bubble pulsation T_1, T_2 depend on a pressure in the shock wave and liquid properties. For example, T_1 = 130-320 us, T_2/T_1 = 0.4-0.5 for tip water at pressure p_M = 0.4 MPa.

MATHEMATICAL MODELING

Experimental data above shows that a dynamics of bubbles is greatly different at the passing of bipolar acoustic wave in cavitating liquids. To reveal reasons of the difference, as well as mechanism of forming of the secondary waves and nature of bubble interaction, modeling of an initiating pulse, moving through the single bubble or through the complex of bubbles, having different initial diameters and situated on a definite distance one from another, is conducted.



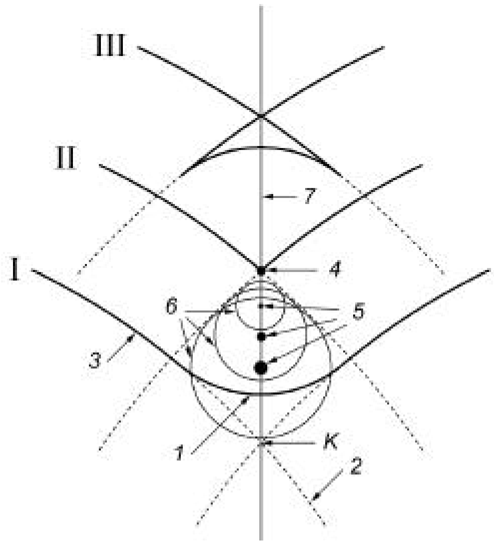


Fig. 1.- Picture of waves and cavitation near the focus.
Fig. 2.- Scheme of wave picture near the focus.

Consider a flow in the round tube filled with water under the initial pressure p_0 = 0,1 Ì Pà Gas bubbles were placed at the tube center with a gas pressure inside equal to p_0. Hence, in the beginning the system of liquid-gas bubbles was in a state of a dynamic balance, and medium velocity was equal to zero. Initiating pulse moved from the left to the right and had a profile of a flat bipolar sinusoidal wave, consisting of the phase of compression and the phase of rarefaction. The length of each phase was 5 mm, the wave amplitude was ±11,5 Ì Pà Between the phases of compression and rarefaction there was a delay, which is variable. Physically it can correspond to the case of a possible reflection of the compression wave from a free surface. In the majority of calculations the length of the delay was 2 mm. The pulse parameters correspond to experimental data stated above. In the definite time interval the pulse passes through the bubbles, system acquires non-equilibrium state with formation of secondary waves. To clarify the mechanism of wave formation and interactions, in some calculations initiating pulse consisted either from the phase of rarefaction, or from the phase of compression only. It is supposed that lateral walls of the tube are closed (rigid wall), the right-hand end is open.

Nature of the pulse, initial location of bubbles and border conditions allow us to consider the flow as an axi-symmetrical one, where an axis of symmetry is the axis of the tube. The origin of coordinate system is on the axis of symmetry at the left end of the tube. A two-phase compressible flow of a liquid with gas bubbles was described by non-stationary two-dimensional Eulerian equations of conservation of mass, pulse and energy. Diffusion effects were not considered.

Bottom edge of the computed area is the axis of symmetry of the tube. Condition of non-penetrating was valid on upper, lower (velocity component $v = 0$) and left ($u = 0$) borders. Border conditions on the right-hand end of the tube corresponded to ones on a free surface. Conditions in bubbles satisfy to an equation of state of an ideal gas. The flow in a liquid is described by two conservation laws of the system (without the law of conservation of energy). To complete the system there were used correlations, depicting shock wave adiabat of water [6].

Given hyperbolic problem was solved numerically using a method of individual particles [7]. Such a problem for a single bubble with chemically reacting gas was considered in [8]. Here a special emphases is done on mutual influence of bubbles. Non-stationary fields of main thermodynamic parameters have been calculated inside each bubble and in external for them flow of liquid as well. It is suggested that border between the liquid and a bubble represents contact surface breakup, on which the following conditions are valid: (i) equalities of pressures on different sides of the breakup and (ii) continuity of medium velocity vector component that is normal to the breakup. In course of time gas bubble can be deformed, crushed and cohered with the others.

RESULTS OF CALCULATIONS

In calculations the following values of specific constants were used: initial liquid density of 1 g/ñm^3; initial gas density of 0,001225 g/ñm^3. Sizes of calculated area: ZxR = 35x4 mm.

In the first calculation we model a bipolar pulse motion in a liquid with a single bubble placed on the z-axis having an initial radius of 0,5 mm. The pulse starts from the left end of the tube, at the moment t = 0,4 µs compresses the bubble, and at t = 2,5 µs abandons its vicinity. The bubble in the compression wave begins to shrink, this process is going on behind the wave due to inertia. The phase of compression lasts till t = 5,0 µs, and the bubble volume decreases approximately in two times. Having passed around the bubble, the compression wave have lost an essential part of its energy, and its amplitude after t = 2,8 µs is approximately equal to 4 Ì Pà A part of its energy is accumulated in the compressed bubble. Besides, reflected from the liquid - gas boundary the primary pulse forms a secondary wave of rarefaction. At t = 4,6 µs the rarefaction wave of the bipolar pulse reaches the bubble. Its reflection from the surface of the bubble, as well as the beginning of bubble expansion result in a formation of a secondary wave of compression. At the moment t = 9,6 µs moving to the right the complex of the initiating bipolar pulse and the secondary wave of compression is formed, and their intensities are comparable. Reduction of an initial radius of the bubble qualitatively does not change the picture of the flow. Processes of reflecting from the bubble's surface plays herewith less significant role, the bubble collapses to a smaller size, that enlarges the amplitude of the secondary wave of compression and reduces its length.

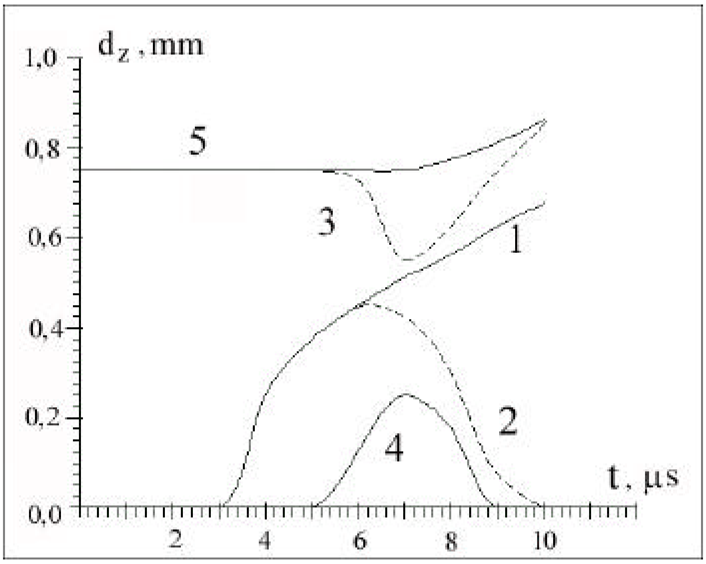


Fig. 3.- Calculated bubble diameter vs time.

Calculated results show that generation of the secondary shock wave (SSW) takes place in the phase of bubble expansion, that is in the rarefaction wave of the bipolar impulse. To clarify the conditions and parameters of SSW, a propagation of a single rarefaction wave (without phase of compression) was modelled in the second calculation. When the wave passes through the medium with a single micro-bubble having an initial diameter of 20 µm, the bubble starts to expand, reaching the value of a mean diameter d = 300 µm for t = 9 µs. Dynamics of changing of the longitudinal diameter d_z is shown in Fig. 3 (line 1).

The third calculation is devoted to a process of bubble generation in liquids with already existing sufficiently greater bubbles. Fig. 3 (dashed lines 2 and 3) and Fig. 4 show results of the modelling. Initial parameters of a falling rarefaction wave and a micro-bubble are the same as for the previous calculation, but on the axis a second bubble is placed on the distance of 3,35 mm measured from the micro-bubble. Dark tones in the Fig.4 correspond to waves of compression, light ones – to waves of rarefaction, wave amplitude corresponds to intensities of the tones. On initial stages a process of micro-bubble expansion runs in the same manner as without the bigger bubble. It becomes to be visible on the plot at the moment t = 3,5 µs. At this time in vicinities of the bigger bubble the wave of compression begins to be formed. Expanding the first bubble generates a secondary wave of compression, which at the moment t = 6 µs reaches vicinities of second one and deforms it (curve 3 in Fig. 3). The micro-bubble reaches its maximum size at t = 6,4 μs (curve 2 in Fig. 3), and its radius becomes comparable in size with the current radius of the bigger bubble. Forming at the interaction of two secondary waves a powerful wave of compression begins to move in the inverse direction to the smaller bubble. The length of the wave is enlarged due to increasing bigger bubble. As a result, collapse of the first bubble occurs, and at t = 10 μs it becomes invisible in the figure. At following moments of the time, the second oscillation of amplitude reaches the amplitude of the first one, but further oscillations are fading. Amplitudes of the non-stationary secondary waves in bubble vicinities are greater than the amplitude of the initiating wave of rarefaction. Though in some moments of the time (t = 6 - 7 us) current sizes of the bubbles turn out to be comparable, the whole described above process is vastly different from a case with a single bubble. As follows, period of the first pulsations of the micro-bubble is vastly reduced.

Note that the bubble surface in the process is unstable, toroidal waves are formed there. They have an irregular structure due to an outward essentially non-stationary flow, caused, in particular, by an influence of walls of the tube. A center of masses of the bubble is not moved significantly for the period specified in the figure.

In the fourth calculation the micro-bubble was placed behind the bigger one. The calculated diameters are shown in Fig. 3 (curves 4 and 5). It follows that phase of expansion of the bigger bubble (curves 3 and 5) complies with the collapse phase of smaller one (curves 2 and 4) regardless of their relative position. If small bubble is disposed in cavitational trace of big one, its maximum size is far less, than for another initial positions. Results of mathematical modelling presented here qualitatively and quantitatively correspond to experimental data shown in Fig. 1, 2. In particular, period of the first pulsation of the micro-bubble coincides with the experiment [10] and is 2-4 μs. Thereby, results of calculations show that in liquids with gas bubbles having different diameters a redistribution of energy occurs. Smaller bubbles collapse in the SSW of greater ones and hereinafter stay invisible, though in some initial periods they can reach quite big sizes.

The similar results have been obtained for bimodal pulses in liquids. In difference from the results in Fig. 3-4, by the moment of passing of rarefaction wave a pressure in bubbles are well above the pressure in surrounding liquid. So, amplitude of secondary waves of compression turns out to be greater than in the second and following calculations.

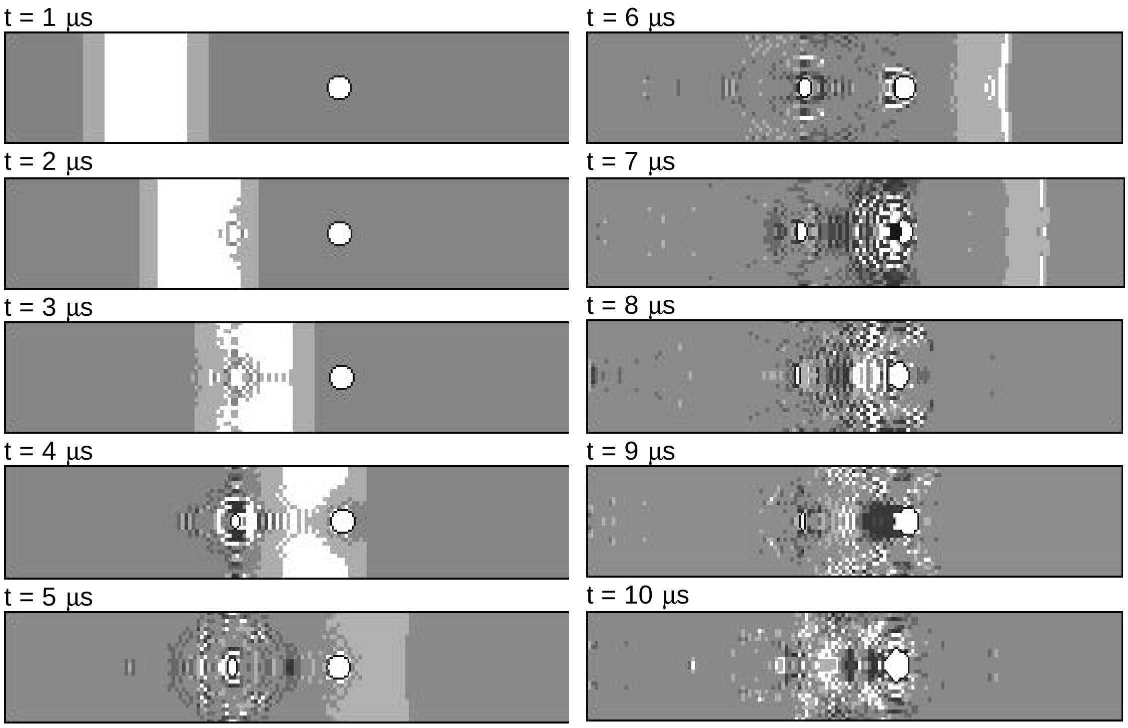


Fig. 4.- Bubble dynamics in rarefaction wave.

DISCUSSION

Shown in the paper is the transformation of rarefaction pulse into compression one during cavitation in focusing acoustic pulse. The general dynamics of bubble is mainly defined by the wave of rarefaction. The further bubble dynamics in a cluster is defined by scattering waves, coming from the nearby bubbles. Performed for a two-fractional cluster, the computational experiment has shown a mechanism of a formation of the secondary cavitational waves. For any relative bubble position in two-bubble system it is found that the secondary acoustic wave is a compression pulse. It was discovered that in a polydisperse cavitational cluster induced by a shock wave, bubble dynamics critically depends on an initial radius of nucleus. If at the initial moment of time close bubbles are in the dynamic balance and have different sizes, a phase of expansion for a bigger bubble coincides with a phase of collapse of a micro one regardless of their relative position. Herewith, if micro-bubble is disposed in cavitational trace of macro one, its maximum size is far less, than under other initial positions. Results of calculations show that in the bubble media with bimodal distribution of the initial size, a redistribution of energy occurs. Small bubble at the expansion "gives" its energy to bigger one, but then its growing is slowed and moves over to collapse due to the influence of secondary wave, coming from the bigger bubble. Presented here results of mathematical modeling are in a good agreement qualitatively and quantitatively with the experimental data.

The process as a whole is similar to the laser breakdown of a liquid [9]. It follows from an analysis of the high-speed photo recording and the calculation that the source of the secondary pulse is a cavitation cluster of bubbles expanding in a rarefaction wave which forms a complex structure of a wave field. Observed in the range of angles from 0 to A = 30-45 degrees are conditions of an amplification due to an interference of discreet spherical waves provided by a supersonic distribution of the front of cavitation. In this solid angle a compression pulse is formed from cavitation in the edge rarefaction wave. A similar effect with A = 38 degrees for a centre of a cavitation cluster was observed in [3] for a plane transducer. The numerical modelling shows a reduction of a period of collapse of probe bubbles. The regime of the pulse compression results in strengthening of the collapse and luminescence in the secondary wave [10].

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