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# INTERACTION OF A SHOCK WAVE WITH A SPHERICAL GAS–LIQUID CLUSTER

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*Experimental studies were performed of the interaction of a plane shock wave with a spherical gas–liquid cluster (polyurethane foam ball saturated with a bubbly liquid) in a vertical shock tunnel filled with a liquid. The cluster was shown to generate a solitary pressure wave of large amplitude.*

**Key words:** *shock wave, bubble cluster, liquid.*

Numerical calculations [1] of the collapse of a layer of cavitation bubbles near a rigid wall revealed the formation of a series of large-amplitude pressure pulses on the wall due to the inertial effects of collective collapse of bubbles. A powerful secondary shock wave arising from collapse of a single bubble in a liquid was observed visually in experiments [2, 3] using optical methods. Enhancement of shock waves in a liquid with vapor bubbles and bubbles of a readily soluble gas was shown in experimental studies [4–8]. The enhancement can take place in both transmitted waves and in waves reflected from a rigid boundary. The generation of high-power pressure pulses by spherical bubble clusters was studied numerically in [9], where the problem was first formulated and the mechanism of enhancement of shock waves by a spherical bubble cluster is explained.

The present paper describes an experimental investigation of the interaction of a plane shock wave with a spherical bubble cluster in a liquid.

The experiments were performed in a shock tunnel type facility. The working area was a vertical thick-walled steel tube with an inner diameter of 53 mm and a length of 1 m. On the axis along the working area there was a stainless steel wire of 1 mm diameter, whose ends were fastened on the rear walls of the working area. The working area was partly filled with a liquid under vacuum, which prevented the formation of gas bubbles in the liquid. The working liquid was distilled water. In the working area, the water was saturated with air to an equilibrium state at room temperature and atmospheric pressure. A bubble cluster — a polyurethane foam ball filled with the bubbly liquid — was put on the wire at the center of the tube. The cluster was located near the bottom of the working area (Fig. 1). The upper edge of the cluster was at 10 mm from the liquid surface. In the experiments, we used polyurethane foam balls with diameters of 30 and 45 mm and a polyurethane foam layer 20 mm high and 53 mm in diameter.

The bubble cluster was prepared on an auxiliary facility as follows. The polyurethane foam ball was placed in the working volume of this facility and was saturated with distilled water under vacuum. Next, air bubbles at elevated (compared to atmospheric pressure) static pressure were passed through the liquid in the working volume. The liquid in the working volume was saturated with air to an equilibrium state at a given static pressure, and, because of diffusion, the gas was dissolved inside the polyurethane foam ball. The time of equalization of the concentration of the gas dissolved in the liquid on the surface and at the center of the ball $\tau$ was a few tens of hours [$\tau \approx R^2/(2D)$ [10], where $R$ is the radius of the cluster and $D$ is the diffusion coefficient]. After release of the static pressure to atmospheric pressure, gas bubbles separated from the liquid, adhered to the polyurethane foam skeleton, and formed a gas–liquid cluster.

We note that the porosity of the polyurethane foam ball was high enough (about 98%) and the stiffness was low; therefore, the porous skeleton did not affect the pressure wave propagation [11].

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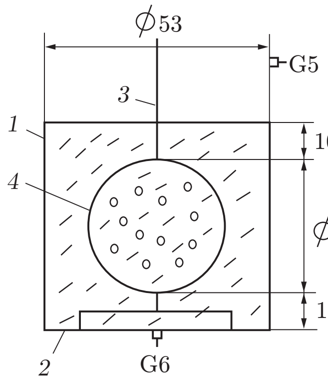

Fig. 1

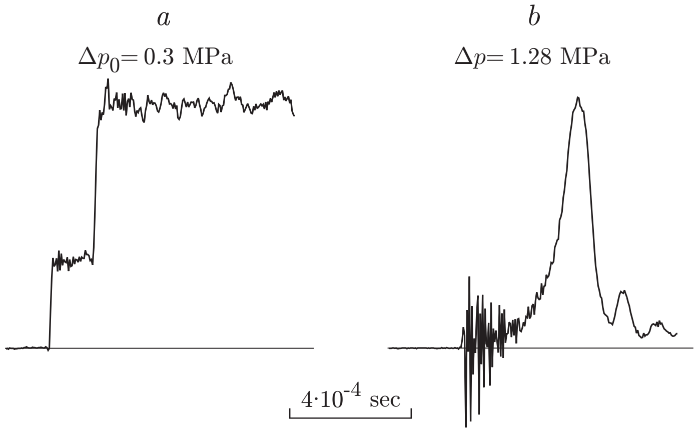

Fig. 2

Fig. 1. Diagram of the location of the bubble cluster in the shock tunnel: 1) working area; 2) bottom of the working area; 3) a steel wire; 4) gas–liquid cluster; G5 and G6 are pressure gauges.

Fig. 2. Profile of an air shock wave entering the liquid (a) and a solitary pressure wave profile in the liquid (b).

Assuming that the nucleation of gas bubbles in the cluster during static pressure release is a heterogeneous process, which is valid for usual distilled water, it is possible to estimate the critical radius of a nucleus with which nucleus growth begins [12]: $a_* = 2\sigma/\Delta p_s$ ($\sigma$ is the surface tension coefficient of the liquid and $\Delta p_s$ is the static pressure difference). In the preparation of the cluster saturated with water containing air bubbles, the pressure $\Delta p_s \geqslant 0.2$ MPa. The critical nucleus size is $a_* \leqslant 10^{-6}$ m. Taking into account that the number of nuclei with the characteristic size $a \approx 10^{-6}$ m in a unit volume of water is $n \approx 10^{12}$ m$^{-3}$ [12], it is possible to estimate the bubble radius to which a nucleus grows during static pressure release. In the examined range of volumetric gas contents, the diameter of air bubbles is usually $d \approx 10^{-4}$ m. However, on the cluster surface, gas bubbles with sizes up to $d \approx 5 \cdot 10^{-4}$ m were observed, which can be due to coalescence of bubbles during their growth after static pressure release.

The initial volumetric gas content in the cluster $\varphi$ can be changed by varying $\Delta p_s$. The mean volumetric gas content in the cluster was determined from an increase in the liquid volume due to a decrease in the initial static pressure in the medium and in the cluster volume [11]. The measurement error of the initial volumetric gas content did not exceed 10%.

When the diaphragm separating the high-pressure chamber and the working area resulted broke, stepped pressure waves formed in air and then propagated in the liquid. The pressure wave profiles were recorded by piezoelectric pressure gauges located on the lateral surface (G1–G5) and at the bottom of the working area (G6). Signals form the gauges were supplied to an analog-to-digital converter and were processed on a digital computer.

Figure 2a shows the profile of an air shock wave entering the liquid ($\Delta p_0$), and Fig. 2b shows the pressure wave profile in the liquid ($\Delta p$). It is evident that the gas–liquid cluster, being compressed under the action of the stepped pressure wave entering the liquid, produces a soliton-like pressure profile in the liquid. The pressure wave amplitude in the liquid far exceeds the amplitude of the wave entering the medium. The formation of the solitary profile is related to absorption of the refracted shock wave by the cluster and subsequent reradiation [9]. The high-frequency oscillations at the leading edge of the wave (Fig. 2b) are due to passage of high-frequency shock-wave pulsations over the liquid and their reflection from the bottom and free surface of the liquid; in addition, they are due to bubble oscillations in the cluster.

Figure 3 gives the pressure wave amplitude in the liquid $\Delta p$ (points 1) versus the amplitude of the shock wave entering the liquid $\Delta p_0$ for the geometry of cluster location presented in Fig. 1 ($p_0$ is the static pressure in the liquid ahead of the shock). It is evident that the amplitude of the pressure wave reradiated by the cluster far exceeds the amplitude of the shock wave entering the medium and increases with increase in $\Delta p_0/p_0$. There is a considerable spread in the values of $\Delta p/\Delta p_0$ for large values of $\Delta p_0/p_0$ due to a decrease in the initial volumetric gas content in the cluster $\varphi$ during the experiment because some bubbles leave the cluster after passage of the large-amplitude pressure wave over the medium. After $\varphi$ decreased by more than 20% of the specified initial value,

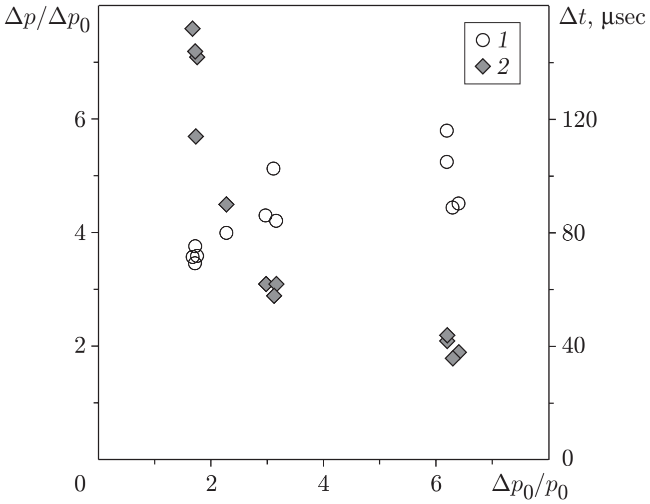

Fig. 3. Relative amplitude (points 1) and half-width (points 2) of a solitary pressure wave in the liquid versus the amplitude of the shock wave entering the liquid ($p_0 = 0.1$ MPa and $\varphi = 12.8\%$).

the experiment was interrupted and a new cluster with specified parameters was prepared. Points 2 in Fig. 3 are experimental data on the half-widths of a solitary wave in the liquid, measured as in the case of a classical Korteweg–de Vries or Boussinesq soliton [13] ($\Delta t$ is the duration of the wave from the value of $0.42\Delta p$ to the maximum wave pressure $\Delta p$). The wave durations obtained for corresponding amplitudes are much larger than the duration of solitons calculated from bubble size in the cluster [13, 14] and are well below the duration of the wave generated by oscillations of a gas bubble whose size is comparable to the cluster size. At small amplitudes of the incident shock wave, a strong dependence of the solitary wave duration on its amplitude is observed. As the values of $\Delta p_0/p_0$ increase, the duration of the solitary wave changes to a lesser extent.

Let us now consider the interaction of a stepped shock wave with a spherical gas–liquid cluster near the liquid surface and the formation of a solitary pressure wave traveling over the liquid. The upper edge of the cluster was at 10 mm from the liquid surface, and the liquid level in the working area was approximately 0.5 m. Figure 4 shows pressure wave profiles in the liquid behind a bubble cluster of 30 mm diameter at different distances $x$ from the entrance of the shock wave into the medium for two values of the initial wave amplitude. The wave profiles given in Fig. 4 were obtained during one experiment. The gauge placed at $x = 0.495$ m from the entrance of the wave into the medium was at the same level as the bottom of the working area and recorded the wave reflected from the bottom. In Fig. 4a, it is evident that the bubble cluster forms a solitary pressure wave from the initial stepped wave; the solitary wave propagates at the velocity of sound over the liquid with nearly unchanged shape and amplitude ($x = 0.105$ and 0.305 m). The amplitude of the solitary pressure wave far exceeds the amplitude of the transmitted shock wave. After reflection from the rigid bottom, the amplitude of the solitary wave increases by almost a factor of two ($x = 0.495$ m). The high-frequency oscillations at the leading edge of the solitary wave are due primarily to oscillations of gas bubbles in the cluster. As the amplitude of the shock wave entering the medium increases, the duration of the solitary wave decreases and its amplitude increases (Fig. 4b). As for solitons of large amplitude in a homogeneous gas–liquid medium [14], the solitary pressure wave profile becomes sharper. An increase in the amplitude of the solitary wave results in an increase in the rate of its damping in the liquid.

Figure 5 shows experimental dependences of the amplitude of the solitary pressure wave formed by a bubble cluster on the amplitude of the shock wave entering the medium for various parameters of a gas–liquid cluster of 30 mm diameter (points 1–4 are data for the amplitude of the solitary wave formed by the cluster and points 5 and 6 are data for the amplitude of the solitary wave reflected from the rigid bottom). The amplitude of the solitary wave formed by the bubble cluster was measured at 105 mm from the entrance of the shock wave into the medium. An analysis of the dependences leads to the conclusion that for small values pf $\Delta p_0/p_0$, the solitary wave amplitude increases and for large values, the relative amplitude $\Delta p/\Delta p_0$ decreases with increase in the amplitude of the shock wave entering the medium. Apparently, in the region $\Delta p_0/p_0 \approx 5$–10 there is a maximum of the relative amplitudes $\Delta p/\Delta p_0$, which agrees with results of the numerical calculations of [9]. From a comparison of the experimental data

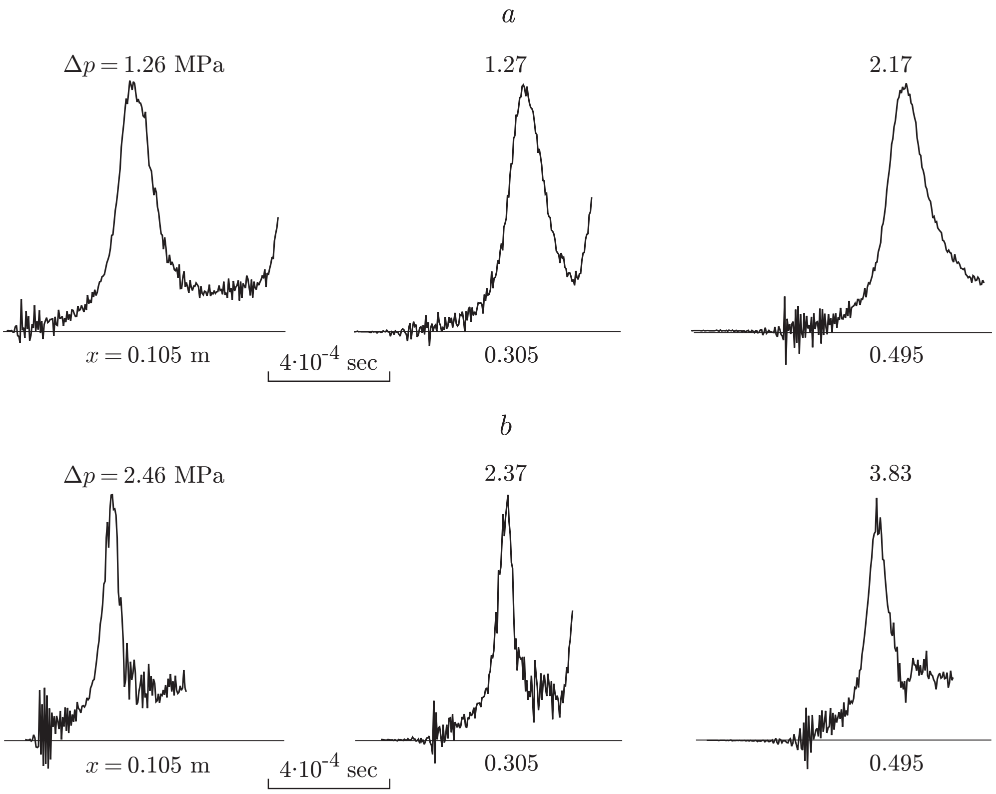

Fig. 4. Pressure wave profiles in the liquid behind a bubble cluster of 30 mm diameter ($p_0 = 0.1$ MPa): (a) $\varphi = 12\%$ and $\Delta p_0 = 0.36$ MPa; (b) $\varphi = 8.9\%$ and $\Delta p_0 = 0.69$ MPa.

(points 1 and 3) for different initial volumetric gas contents $\varphi$, it follows that an increase in $\varphi$ in the cluster leads to an increase in the solitary wave amplitude. A rise in the initial static pressure in the cluster ahead of the wave also increases the solitary wave amplitude (compare points 3 and 2). A reduction in $p_0$ and a rise in $\varphi$ in the cluster increases the compressibility of the cluster, resulting in more intense compression of the cluster in the shock wave and an increase in the solitary wave amplitude. Upon reflection from the rigid wall, the solitary wave amplitude increases by a factor of almost two (points 3 and 5 and points 4 and 6, respectively). The greatest departure from this regularity is observed for large wave amplitudes (points 3 and 5), which is due to dissipative losses during the evolution of the wave in the liquid.

Figure 6 gives experimental data on the half-width of the solitary wave in the liquid versus the amplitude of the shock wave entering the medium for different parameters of a gas–liquid cluster of 30 mm diameter. It is evident that the duration of the solitary wave decreases with increase in the amplitude $\Delta p_0/p_0$. For small values of the shock wave amplitude, there is a strong dependence of $\Delta t$ on the initial volumetric gas content $\varphi$ and the static pressure ahead of the wave $p_0$. As $\varphi$ increases (points 1 and 3) and $p_0$ decreases (points 3 and 2), the duration of the solitary wave increases. This is due to the fact that for small values of $\Delta p_0/p_0$, the time of compression of the cluster and the duration of the cluster-generated solitary wave are determined primarily by the time of passage of the refracted shock wave through the cluster. As the amplitude $\Delta p_0/p_0$ increases, the inertial properties of the cluster begin to play an increasingly important role in the compression of the cluster. For $\Delta p_0/p_0 > 6$, the duration of the solitary wave practically does not depend on the cluster parameters $\varphi$ and $p_0$ and is determined by the wave amplitude, as in the case of solitons in bubbly media [13, 14].

Figure 7a shows pressure wave profiles in the liquid behind a bubble cluster of 45 mm diameter at $x = 0.105$ m from the entrance of the shock wave into the medium and near the bottom of the working area ($x = 0.495$ m). It is evident that when the cluster reaches a size close to the inner diameter of the working area of the facility, the structure of the solitary wave formed by the cluster changes. The duration of the solitary wave increases as the

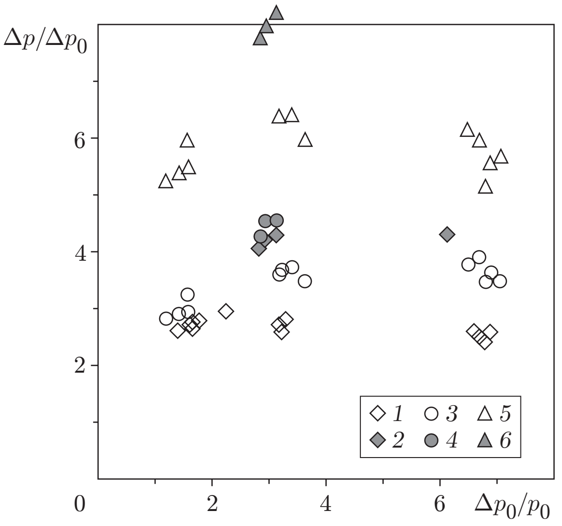

Fig. 5

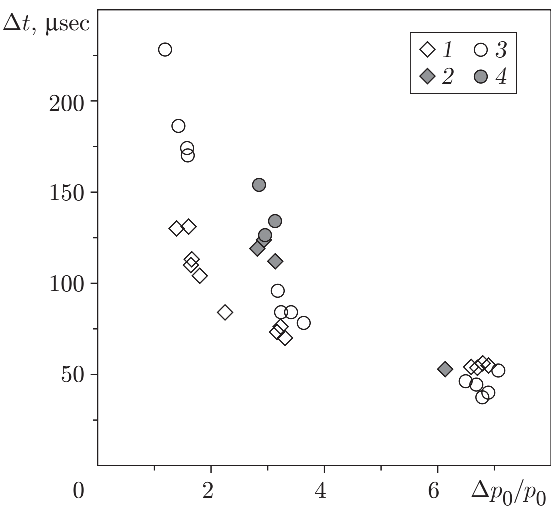

Fig. 6

Fig. 5. Relative amplitude of the solitary pressure wave formed by a bubble cluster of 30 mm diameter versus the amplitude of the shock wave entering the medium: 1) $p_0 = 0.1$ MPa and $\varphi = 4.8\%$; 2) $p_0 = 0.05$ MPa and $\varphi = 11.2\%$; 3) $p_0 = 0.1$ MPa and $\varphi = 12\%$; 4) $p_0 = 0.05$ MPa and $\varphi = 24\%$; 5) $p_0 = 0.1$ MPa and $\varphi = 12\%$; 6) $p_0 = 0.05$ MPa and $\varphi = 24\%$.

Fig. 6. Half-width of the solitary pressure wave in the liquid versus the amplitude of the shock wave entering the medium: 1) $p_0 = 0.1$ MPa and $\varphi = 4.8\%$; 2) $p_0 = 0.05$ MPa and $\varphi = 11.2\%$; 3) $p_0 = 0.1$ MPa and $\varphi = 12\%$; 4) $p_0 = 0.05$ MPa and $\varphi = 24\%$.

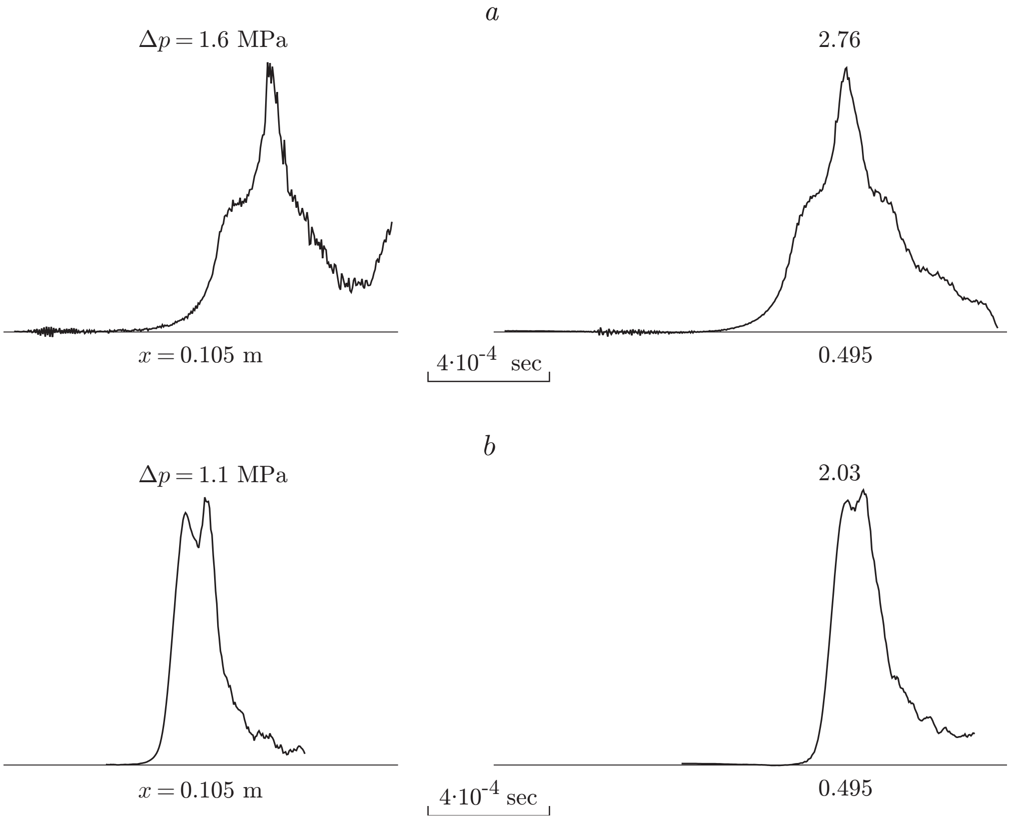

Fig. 7. Pressure wave profiles in the liquid ($p_0 = 0.1$ MPa and $\Delta p_0 = 0.3$ MPa) behind a spherical cluster of 45 mm diameter ($\varphi = 9.2\%$) (a) and behind a flat layer ($\varphi = 8.8\%$) (b).

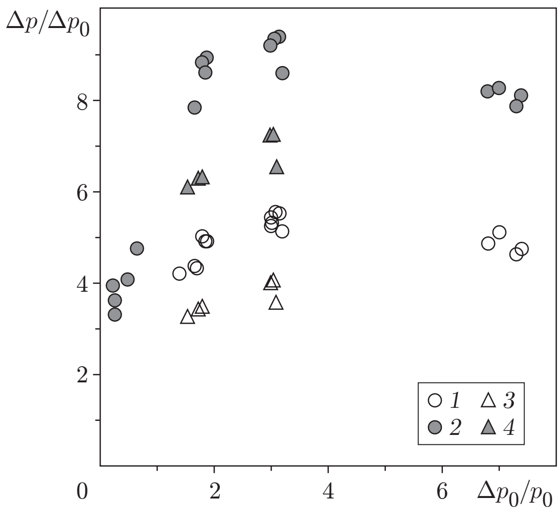

Fig. 8. Relative amplitude of solitary pressure waves in the liquid ($p_0 = 0.1$ MPa) behind a spherical cluster of 45 mm diameter ($\varphi = 9.2\%$) (points 1 and 2) and behind a flat layer ($\varphi = 8.8\%$) (points 3 and 4); points 1 and 3 refer to amplitude of the transmitted wave and points 2 and 4 refer to amplitude of the wave reflected from the bottom.

cluster size grows, and the wave front has a distinct point of inflection. Thus, at a particular stage of the process of cluster compression by a shock wave, the pressure behind the cluster almost ceases to increase in a rather long time interval and then increases sharply again. A similar picture is observed at the trailing edge of the solitary wave during stretching of the cluster. This wave structure can be due to the effect of the rigid wall on cluster oscillations. During compression of the cluster, the liquid flow to the cluster from the lateral surface of the working area is bounded by the wall. Hence, there is a liquid flow along the cluster surface from the center of the working area to the lateral surface and the process of cluster compression slows down.

Figure 7b shows pressure wave profiles in the liquid behind a flat polyurethane foam gas–liquid layer with a diameter equal to the diameter of the working area and with a height of 20 mm. As in the case of a spherical cluster, enhancement of the wave is observed during passage through the gas–liquid layer. However, the wave amplitude is determined by the reflection law on the boundaries of the gas–liquid layer, and the duration is determined by the time of travel of the compression and rarefaction wave over the layer.

The experimental dependence of the amplitude of the solitary pressure wave formed by a bubble cluster of 45 mm diameter on the amplitude of the shock wave entering the medium is given in Fig. 8 (points 1). The same figure shows data on the amplitude of the solitary pressure wave reflected from the rigid bottom (points 2). It is evident that the nature of the dependence does not change as the cluster size increases. From a comparison of the experimental data given in Fig. 8 (points 1 and 2) and in Fig. 5 (points 3 and 5) for close values of the initial volumetric gas content and static pressure ahead of the wave, it follows that an increase in the cluster size leads to an increase in the amplitude of the solitary pressure wave formed by the cluster.

For comparison, Fig. 8 gives experimental data for the wave in the liquid behind a flat polyurethane foam layer with a diameter equal to the diameter of the working area and with a height of 20 mm (points 3 refer to the wave formed by the layer and points 4 refer to the wave reflected from the rigid bottom). On can see an increase in the wave amplitude, as in the case of a spherical cluster. However, the wave amplitude behind the flat layer is smaller than that behind a spherical cluster of the same volume (points 1 and 3).

Thus, it is shown that the interaction of a plane shock wave with a spherical bubble cluster in a liquid results in generation of a solitary pressure wave with an amplitude far exceeding the shock wave amplitude. It is established that the structure of the solitary pressure wave is determined not only by the cluster parameters and the shock wave amplitude but also by the ratio of the diameters of the cluster and the working area.

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