EXPERIMENTAL STUDY OF THE INTERACTION OF PRESSURE WAVES OF MODERATE INTENSITY IN A LIQUID WITH GAS BUBBLES

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There has recently been an increased amount of attention devoted to the study of the propagation and interaction of nonlinear wave-solitons in different media having dispersive properties [1, 2]. One such medium – which exhibits pronounced nonlinearity and dispersion – is a liquid containing gas bubbles [3, 4]. An experimental study was made in [5] of the interaction of two solitons of small amplitude $\Delta p/p_0 < 1$ in a gas–liquid medium in the case when one soliton overtakes the other, as well as the case when two solitons interact upon encountering one another.

The goal of the present study is to experimentally investigate the evolution of solitary compression waves of moderate intensity when they meet one another or when they interact with a large bell-shaped wave in a liquid with gas bubbles.

The experiments were conducted on the shock tube described in [6]. The working section was filled with a water–glycerine solution and saturated with air bubbles (gas content in all of the tests $\varphi_0 = 3 \cdot 10^{-3}$). The initial pressure pulses were formed at both ends of the working section and then propagated in toward one another. They were bell-shaped and were created by different methods. The pulse at one end of the working section was created by the mechanical impact of a piston against the liquid [6], while the other pulse was generated – with the requisite lag – by an electromagnetic method. The signal was formed when a thin copper plate located at the boundary of the gas–liquid mixture was driven back by an electromagnetic coil. The parameters of the initial pressure wave changed with variation of the amplitude and duration of the current pulse that was passed through the coil.

Pressure profiles were recorded with piezoelectric pressure transducers located along the working section. The electrical signals from the transducers were directed through high-impedance amplifiers to ATsP-10/1 digitizers installed in a standard KAMAK unit based on an "Élektronika-60" computer. The signals were then sent to a monitor and graph plotter and were analyzed.

Figure 1a shows the evolution of a compression wave in a liquid with gas bubbles of the radius $R_0 = 1.5$ mm. The figure shows the evolution of the wave along the working section. It is evident that a solitary wave is formed from the initial bell-shaped signal, the amplitude of this wave being considerably greater than the amplitude of the oscillations which follow it. Dissipative losses subsequently cause a decrease in its amplitude and, thus, an increase in its period. Figure 1b shows profiles of solitary compression waves of different initial intensities when they meet at different distances x_i from the point where the waves enter the gas–liquid medium (x_1 for wave 1, x_2 for wave 2). It is evident from a comparison of the oscillograms that the structure and decay of solitary wave 2 in Fig. 1b after interaction with the opposite wave correspond to the evolution and structure of the solitary wave of approximately the same intensity in Fig. 1a.

Thus, in the counter interaction of solitary waves of moderate intensity, no energy is pumped from one wave to the other and the waves are left with the same parameters as before the interaction.

Figure 2 shows the evolution of compression waves in the case of counter interaction in a liquid with gas bubbles. The moment of superposition of the waves was fixed by the transducer located at $x_2 = 390$ mm. In contrast to the interaction of low-intensity ($\Delta p/p_0 < 1$) solitary waves [5], the amplitude of the wave obtained from the union of the two given waves is considerably greater than the sum of the waves before the interaction ($\Delta p_C = \Delta p_1 + \Delta p_2$). This is apparently due to the fact that during the superposition of the waves,

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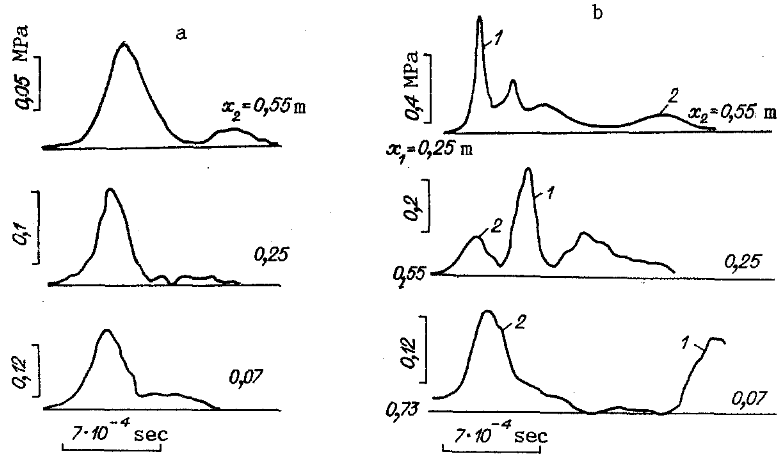

Fig. 1

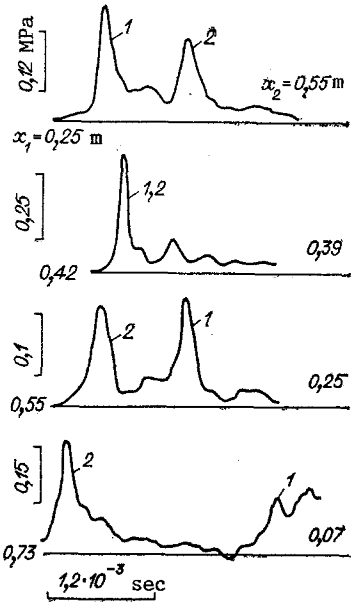

Fig. 2

there is sufficient time for the bubbles to form a new solitary wave on the first two waves. The amplitude of the new wave is 1.5-2 times greater than Δp_C. Numerical calculations [4] have also shown a nonlinear interaction between solitary waves at the moment of collision — although the form of the new wave differs substantially from the form of a soliton of the same intensity. It should be noted that the initial signal generates not only the base soliton, but also several subsequent low-amplitude waves. These waves are superimposed on the counter soliton and introduce an additional error into the measurement of the soliton's amplitude.

It was shown in [6] that the decay of solitary waves of moderate intensity can be generalized by means of the empirically established parameter $H = (\Delta p/p_0)^{0,67}(\Delta x/R_0)\left(\varphi_0 a_0/\omega_R R_0^2\right)^{0.5}$ (φ is the volumetric gas content; a is the thermal conductivity of the gas; ω_R is the frequency of resonance vibration of the bubbles). Figure 3 shows a graph depicting the attenuation of solitary waves in the case of counter interaction in a liquid with gas bubbles. Points 1 represent data for weak compression waves (Δp = 0.1-0.2 MPa), points 2 show the results for stronger waves (0.2-1 MPa), and the lines delineate the region of experimental results from [6] on the decay of solitary waves. It is apparent that the decay of the solitary waves is the same with and without interaction throughout the investigated range of amplitudes $1 < \Delta p/p_0 < 10$. The large scatter of the experimental data is due to the additional error caused by the superposition of the base solitary wave on

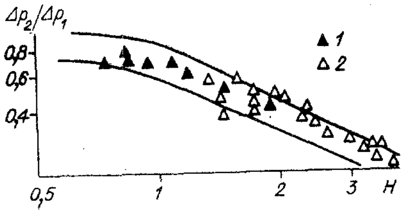

Fig. 3

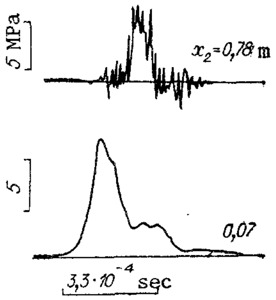

Fig. 4

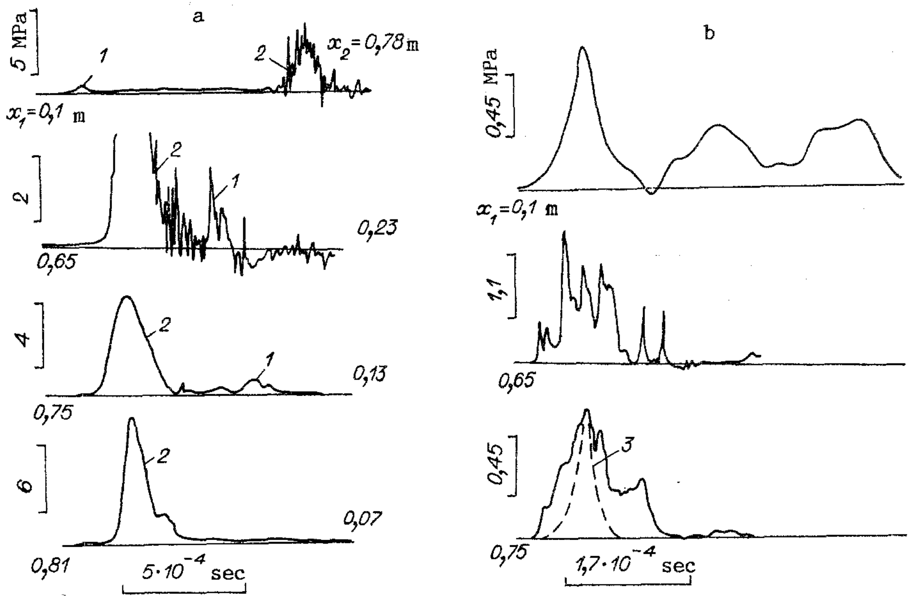

Fig. 5

a wave generated by the initial signal after the soliton. Thus, solitary waves of moderate intensity in a liquid with gas bubbles continue to act as solitary waves after their interaction.

Let us now proceed to examination of the counter interaction of a solitary wave with a high-intensity bell-shaped compression wave. Figure 4 shows the evolution of the compression wave in a gas—liquid medium with a low gas content (φ_0 = 0.3%) and p_0 = 0.1 MPa, R_0 = 1.5 mm. It is evident that the smallness of φ_0 keeps solitons from being formed from the initial signal as it passes through the working section. The signal is covered by high-frequency pressure pulsations from bubbles that break up in the wave. The signal decays slightly, while its shape remains nearly unchanged.

Figure 5a shows characteristic oscillograms of the evolution of solitary wave 1 in a counter interaction with a high-amplitude bell-shaped pressure pulse 2. The parameters of the medium are the same as in Fig. 4. It is evident from a comparison of Figs. 4 and 5 that, other conditions being equal, the amplitude of the bell-shaped signal at x_2 = 0.780 m is substantially less in Fig. 5 than in Fig. 4. Thus, the interaction of a soliton with a wave of arbitrary profile leads to an exchange of energy between them. In the given case, energy is pumped from the more intensive bell-shaped wave to the lower-amplitude solitary wave. With a larger scale, Fig. 5b shows the evolution of the solitary wave in Fig. 5a. One feature of the behavior of the soliton is that its interaction (x_1 = 650 mm) it follows not only by an increase in its amplitude, but also by a change in its shape. The width of the wave is determined by the duration of the bell-shaped signal, while the high-frequency pressure pulsations are due to vibrations of small gas occlusions formed after the fragmentation of bubbles in the bell-shaped compression wave. The propagation of this wave is accompanied by its decay and smoothing of the high-frequency oscillations (x_1 = 750 mm). It should be noted that the wave decays more rapidly in a medium with

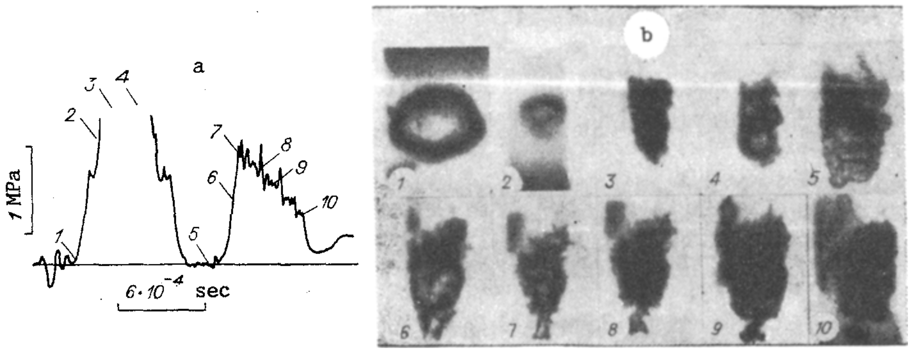

Fig. 6

fragmented bubbles. This is probably related to the fact that, given a constant gas content, a decrease in the size of the gas occlusions is accompanied by an increase in heat transfer from the gas bubbles to the liquid. Line 3 shows the form of the soliton for the given wave intensity and the given parameters of the medium. It is evident that the form of the wave differs substantially from the form of the soliton, i.e., weak dispersion and dissipation in the medium (which contains fragmented bubbles) keeps solitons from forming.

During the tests, we changed the amplitude and length of the solitons within broad ranges. Despite this, the amplitude of the waves always remained nearly the same after the collision. This means that the size of the energy increment depends only slightly on the amplitude of the solitary wave and is determined mainly by the amplitude and length of the more intense bell-shaped profile.

It was shown in [7] that when a large-amplitude wave passes through a gas—liquid medium, the bubbles are broken up into a cloud of very small gas occlusion-clusters. This fragmentation occurs as a result of the relative motion of the gas bubbles in the compression wave. We made a study of the behavior of such clusters during wave propagation. The bubbles were broken up by a bell-shaped high-amplitude pressure pulse. Then, after the necessary delay, the second wave was directed into the medium. The behavior of the bubbles was recorded with the use of a special optical attachment for the working section. The record was obtained with a VSK-5 camera operating at a speed of 40,000 frames/sec in light provided by a flash lamp.

Figure 6b shows the film record of the behavior of a gas bubble in both compression waves at the moments of time designated by numbers on the wave profile (Fig. 6a). It is apparent that the light flash coincides with the breakup of the bubbles into a cloud of very small bubbles. The latter bubbles do not subsequently decrease further in size to any significant extent. Under the influence of the second wave, the pressure of the cluster decreases and the cluster's behavior begins to correspond to the pressure change in the wave. After passage of the wave, the cluster returns to its original size and does not undergo further oscillation. This indicates that the cluster as a whole lacks elasticity and resonance properties.

Thus, a medium with fragmented drop-clusters loses its previous dispersive properties. Dissipation and nonlinearity remains the main parameters that determine the structure of a wave in such media.

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