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MECHANICS

Method of Resonance Overcompression in a Bubble Liquid by a Moderate Aperiodic Action

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Several years ago, the phenomenon of sonoluminescence, that is, the luminescence of gas bubbles in an acoustic field, was discovered [1, 2]. This phenomenon is of interest not only from the scientific point of view; it also has a number of important applications for practice. For example, the appearance of such a direction in chemical technology as sonochemistry is associated with the discovery of sonoluminescence. By virtue of the appearance of high temperatures in bubbles, the acoustic field can initiate certain chemical reactions which are impossible under other conditions. But the most impressive fact is that a nuclear-fusion reaction can be initiated in bubbles at superhigh temperatures. Deuterium bubbles in heavy water at overcompressions can release thermonuclear energy (“bubble nuclear fusion”), but a routine ultrasound is not sufficient to make this take place.

In recent years, a number of studies [3–11] were devoted to the theoretical description of the behavior of an individual gas bubble vibrating in a liquid under a wave-field action provided that the pressure and temperature in the gas can reach extremely high values. The principal idea of the new approach [7], referred to as the “basketball” mode, is the coordination of the process of varying the pressure in a liquid with the forced vibrations of a bubble and the use of a nonlinear resonance during an aperiodic action of an external field of a moderate-amplitude pressure. To realize this idea, we formulated and solved the problem of spherically symmetric vibrations of a gas bubble in a compressible liquid [8–10]. On the basis of the analytical solution obtained, we developed an efficient computer code for the mathematical simulation of the bubble collapse with allowance for various dissipative mechanisms, such as viscosity, heat conduction, radiation, ionization, wave processes around and inside the bubble, and heat-and-mass exchange between the bubble and the ambient liquid under overcompressions of the bubble.

The investigation of the processes taking place in an individual collapsing bubble is obviously an important and necessary stage; however, the above applications are associated with a bubble liquid, i.e., a mixture of carrier liquid with a large quantity of bubbles dispersed in it.

In this study, we propose a method for processing a limited volume of the bubble liquid by an aperiodic moderate-amplitude wave action, as a result of which waves arise with amplitudes exceeding that of the initiating action by several orders of magnitude. This method is illustrated by the results obtained from a direct numerical simulation.

We consider a cylindrical volume of bubble liquid, which has the length L bounded by solid walls and a mobile piston (Fig. 1).

The basketball mode for the excitation of the gas–liquid-mixture is realized by means of specifying the following boundary condition at the piston:

$$p_{\mathrm{p}} = \begin{cases} p_{\max}, & v_{\mathrm{p}} \geq 0 \\ p_{\min}, & v_{\mathrm{p}} < 0, \end{cases}$$

where p_{p} and v_{p} are the pressure and velocity of the medium at the piston. In such a situation, the waves traveling from the piston to the wall, the waves reflected from the wall and traveling back to the piston reflected from it, etc. propagate in the bubble mixture.

For the numerical investigation of the problem formulated, we use the model of the dynamic behavior of a bubble liquid and the method of its computer realization outlined in [12].

In Fig. 2, we show the time dependences for the pressure at the piston, the piston velocity, and the gas pressure in bubbles in the middle of the volume ($x = L/2$) calculated for the case of the basketball and wave ($p_{\mathrm{p}} = p_{\max}$) modes of excitation of the hydrogen–glycerin bubble mixture with the parameters $a_0 = 1$ mm,

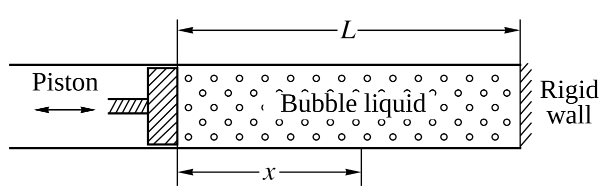

Fig. 1. Schematic of the piston excitation for a bubble liquid.

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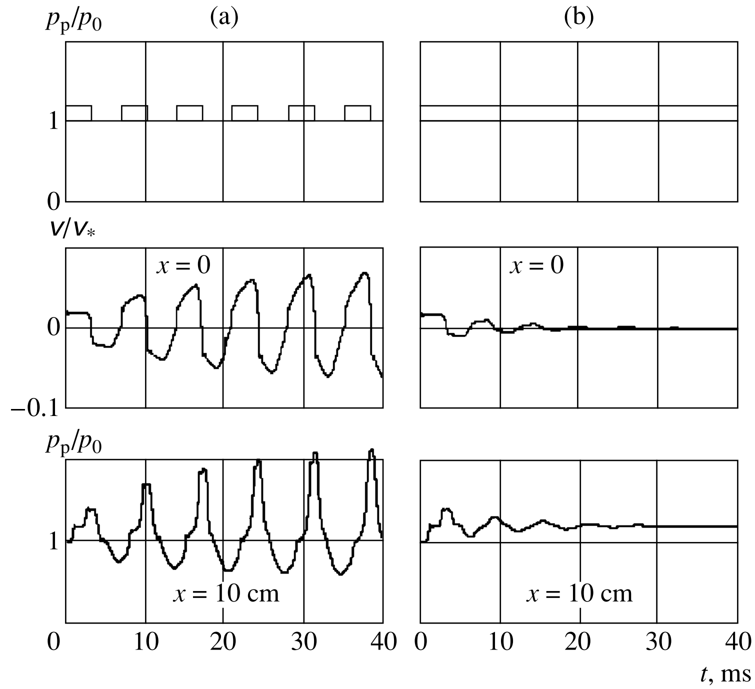

Fig. 2. Profiles of liquid and gas pressures and piston velocities for (a) basketball mode and (b) steady-state mode of bubble-liquid excitation.

$\alpha_0 = 2\%$, $T_0 = 293$ K, $L = 20$ cm, $p_0 = 10^5$ Pa, $p_{max} = 1.2p_0$, $p_{min} = p_0$, and $v_* = \sqrt{p_0/\rho_l}$, where a, α, ρ, T, and p are the radius and volume content of the bubbles, the density, temperature, and pressure, respectively. The subscripts l and g denote the liquid and gas parameters, and 0 implies the initial values of the parameters.

It can be seen (Fig. 2) that the maximum gas pressure in the bubbles grows for the basketball mode of the piston motion during each subsequent travel of a wave, whereas for a constant pressure at the piston (a step-like wave), the gas pressure in the bubbles tends to the pressure at the piston.

Figure 2 confirms the fundamental possibility for excitation of overcompression in a bubble mixture by means of an aperiodic moderate-amplitude action.

The mechanical system under consideration exhibits a resonance. Comparing the eigenfrequencies of this vibrating system and those of the bubble vibrations in the mixture, it is possible to estimate the system parameters for which the excitation mode is resonant.

The eigenfrequency ω_S of the system for the wave excitation can be estimated as

$$\omega_S = \frac{2\pi}{T}, \quad T = \frac{L}{D_S} + \frac{L}{D_R},$$

where D_S and D_R are the velocities for the wave traveling from the piston and the wave reflected from the wall, respectively. Their values can be calculated in the equilibrium approximation from the formulas

$$D_S = \sqrt{\frac{p_{max}}{\alpha_0 \rho_l}}, \quad D_R = \sqrt{\frac{p_R}{\alpha_S \rho_l}},$$

$$p_R = \frac{p_{max}^2}{p_0}, \quad \alpha_S = \frac{\alpha_0 p_0}{p_{max}},$$

where α_S is the volume gas content behind the incident wave and p_R is the pressure behind the wave reflected from the wall.

The eigenfrequency ω_R of the bubble vibrations in the mixture can be determined from the formula

$$\omega_R = \frac{1}{a}\sqrt{\frac{3\gamma p_{max}}{(1-\varphi)\rho_l}}, \quad \varphi = \frac{1.1\alpha_0^{1/3} - \alpha_0}{1-\alpha_0},$$

where γ is the gas adiabatic index and φ is the correction taking into account the fact that the bubbles are not single.

Equalizing the frequencies ω_S and ω_R, we can find the resonance values of the parameters. As can be seen from the formulas, one of the parameters (a_0, α_0, L, p_{max}) is determined by the resonance condition from the given values of the remaining parameters (for the chosen liquid and gas).

In Fig. 3, we display the calculated oscillograms for pressure in the liquid, pressure and temperature in the gas bubbles, the radius, and the volume content of the bubbles situated in the middle of the volume ($x = L/2$) for the resonance excitation of a water–air gas–liquid

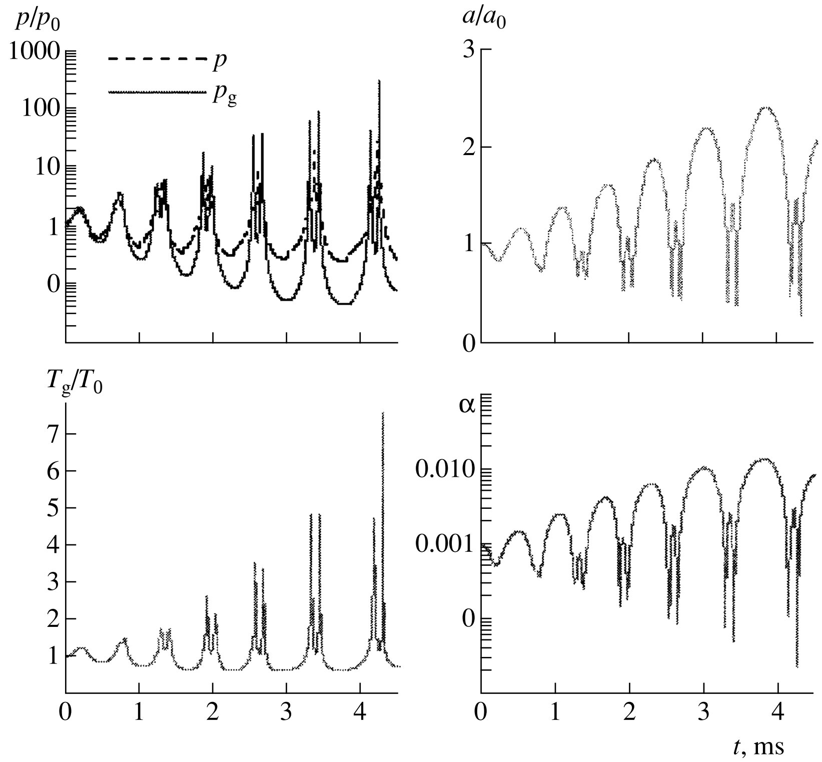

Fig. 3. Profiles of liquid and gas pressures, radius, temperature, and volume concentration of bubbles in the case of the resonance excitation.

mixture with the parameters $a_0 = 1$ mm, $\alpha_0 = 0.1\%$, $T_0 = 293$ K, $L = 5$ cm, $p_0 = 0.1$ MPa, and $p_{max} = 1.5p_0$. It can be seen that, in this case, the pressure amplitude is two orders of magnitude higher than that of the initiating pulse, whose amplitude is only 0.05 MPa. As this takes place, the gas temperature increases to a value higher than 2000 K for a short time. The time dependences for the bubble radius a, radial velocity w, and volume concentration α show that the amplitudes of their vibrations increase with time.

The wave properties of the bubble liquid have been relatively well studied. The behavior of shock waves depends on the choice of carrier liquid phase (its density and viscosity), but is to a greater extent determined by the dispersed phase, even when it is small not only in mass, but also in volume. The gas properties in bubbles, their size, and the character of the interphase heat exchange can radically influence the structure of the shock wave.

The numerical analysis carried out showed that with decreasing the radius of the bubbles the response of the bubble mixture is enhanced in the resonance-excitation mode. This fact agrees with the conclusion obtained in [10] for an individual bubble.

Thus, we have proposed the method of the resonance excitation of a bounded volume of a bubble liquid by an aperiodic moderate-amplitude action, as a result of which extremely high pressures and temperatures can be achieved for a gas in bubbles. This fact is qualitatively illustrated by the profiles of the pressure, temperature, bubble radius, etc. calculated in terms of the single-velocity two-temperature model with two pressures in the bubble mixture with an incompressible liquid phase. In order to obtain more exact quantitative information associated with particular applications, e.g., with the problem of bubble nuclear fusion, it is necessary to develop more complicated models of bubble liquids, which take into account various dissipative mechanisms, such as the compressibility of the liquids, radiation, ionization, wave processes around and inside individual bubbles, etc.

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