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Propagation of powerful acoustic pulse with shock front in relaxing liquids

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ABSTRACT

Shock wave propagation in relaxing fluid is studied theoretically and experimentally. Modified spectral method is used in numerical simulations to provide an accurate description of weak shocks. For the medium with only one relaxation time, the waveforms of initially triangular pulse with shock front are calculated at various distances. It is shown that nonlinearity results in additional increasing of pulse duration and additional suppression of shock front damping. Experiments are performed in acetic acid as a monorelaxing medium. . Short pulses are excited by optoacoustic source. A relaxation time of the fluid is changed by temperature variation. It is shown that pulse distortion is sensitive to the temperature of the medium. A relaxation time is evaluated from the analysis of shock pulse waveform after passing a layer of acetic acid. Theoretical and experimental results are in a good agreement.

INTRODUCTION

The problem of intense wave propagation in liquids or gases with relaxation processes is a classical problem of nonlinear acoustics. Finite amplitude effects in such media are influenced by the dispersion of sound velocity and absorption coefficient. The effect of the relaxation is of particular interest for short acoustic pulses, when the duration of pulse is of the same order as the characteristic relaxation time. The initial waveform in this case becomes strongly distorted even for the low amplitude signals. Theoretically, this process can be described by impulse response function. It appeared that the pulse can be considered as a sum of two waves — forerunner and signal body. Forerunner has the same waveform as the initial pulse. It propagates with the high-frequency sound speed $\mathbf{c}_\infty$, and decays quickly. The signal body propagates slower, with the velocity of low-frequency components in the pulse spectrum. It is closed to the velocity of pulse propagation in an equilibrium medium c_0 . This theoretical result was confirmed in our previous experiments [1], where the pulse amplitude was small enough and nonlinear effects were not so important. In this paper the results regarding the shock wave propagation in the relaxing liquid are presented.

THEORY

To analyze the finite amplitude wave propagation in the relaxing medium the evolution equation (1) is used. It takes into account the effects of nonlinearity, relaxation and termo-viscous attenuation [2]. The kernel in integral term corresponds to classical dispersion law of a relaxation medium.

$$\frac{\partial p}{\partial x} - \frac{\varepsilon}{c_0^3 \rho_0} p \frac{\partial p}{\partial \tau} = \frac{b}{2c_0^3 \rho_0} \frac{\partial^2 p}{\partial \tau^2} + \frac{m}{2c_0} \frac{\partial}{\partial \tau} \int_{-\infty}^{\tau} \frac{\partial p}{\partial \tau'} exp(-(\tau - \tau') / \tau_{rel}) d\tau' \qquad (1)$$

where $\tau = t - x / c_0$ — is the time in retarted coordinate system, ρ_0 — density of equilibrium medium, p — sound pressure, ε — nonlinear parameter, τ_{rel} — relaxation time, b — coefficient of termo-viscous attenuation, $m = (c_\infty^2 - c_0^2) / c_0^2$ — parameter, that characterizes the relaxation strength.

This equation was integrated numerically in the frequency domain. A new shock capturing spectral approach was employed, that permitted to consider wave profiles with discontinuities like shocks [3]. General idea of this method, which is represented in details in [3], is the following. We seek a solution of Eq. (1) in the form of a Fourier series expansion, then an infinite set of coupled nonlinear differential equations for the amplitudes of harmonics can be derived. Numerical solutions of this set of equations are usually obtained by truncating the infinite series on the right-hand side of equations, correspondent to nonlinear term, at some chosen number *N*. The amplitudes of harmonics with numbers $n>N$ thus automatically are assumed to be zero, and a large number of harmonics must be included in numerical calculations to accurately model the propagation of strongly distorted nonlinear waves containing shocks.

The modification of the direct truncation is based on the known high-frequency asymptote of the wave that contains a shock. The presence of a singularity as a step shock in a wave profile results in formation of a slow decaying high frequency asymptote, proportional to $1/n$, the same as for the periodic sawtooth wave with the same amplitude and position of the shock. This asymptote provides a main term in high-frequency series expansion of the entire arbitrary shock wave spectrum. A number of equations therefore can be truncated at $n=N$, however, the infinite series on the right-hand side can be retained. The amplitudes of harmonics with $n>N$ are approximated at each step of numerical calculations by the coefficients of correspondent sawtooth-like wave, thus an analytical summation of the infinite series is provided. The values for the amplitude and shock arrival are derived at every step also on the assumption that the parameters of the last harmonics belong to this asymptote. The waveform at a certain distance then can be expressed as a sum of harmonics, calculated numerically, and the sawtooth waveform.

NUMERICAL RESULTS

The liquid being studied here is a strong acetic acid with relaxation time τ_{rel} varying from 60 to 300 ns with temperature. Another parameters used in calculations are: $\mathbf{m}=0.03$, $\varepsilon=4$ [4], $\mathbf{c_0}=1150$ m/s, $\rho_0=1.05$ g/cm^3 [5]. Coefficient of termo−viscous attenuation **b** was obtained from the experimental frequency dependence of ultrasound attenuation in acetic acid [6]. Its value is approximately 0.01 Pa×s, therefore the termoviscous term in equation (1) is significant only for frequency pulse components higher than 10 MHz. The presence of this term thus does not influence the waveform of the pulse body, however it results in the shock front smoothening.

Figure 1 shows the calculated temporal profiles of nonlinear pulse after passing the acetic acid layers of different thickness. The initial waveform for numerical modeling was chosen as a triangular pulse with the amplitude and duration being the same as in experiment (Fig.2). It is seen that the modified spectral approach used here permits to reconstruct the waveform with infinitely thin shock front. Peak pressure amplitude was 40 bar and pulse duration amplitude at a pulse basis was 270 ns.

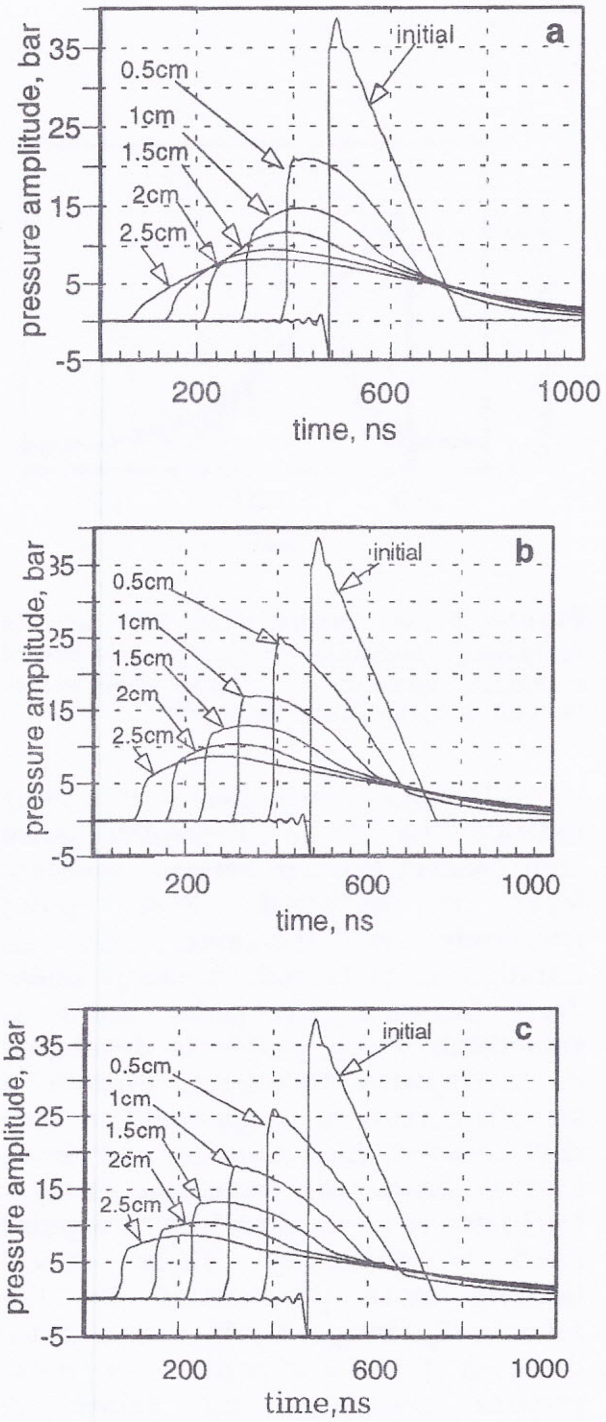

Figure 1 Calculated pulse profiles after passing the acetic acid layers of various thickness (numbers near the curves). a – τ_{rel} = 155 ns, b – τ_{rel} = 110 ns.

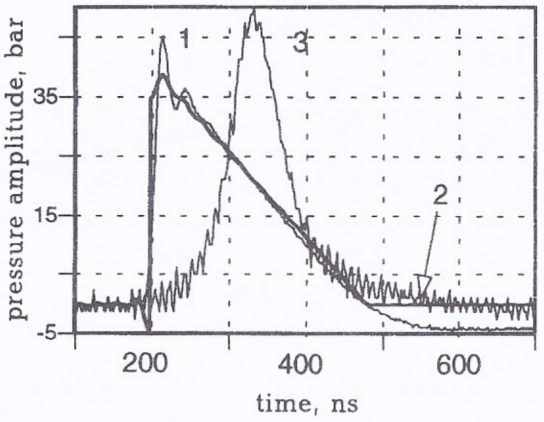

Figure 2 Experimental pulse (1) and its computing simulation (2) at the entrance of a relaxing medium. 3 — pulse waveform at the exit of optoacoustic generator.

Results presented at Fig.1 indicate that initial triangular pulse after passing through relaxing medium layer is distorted. Peak pulse amplitude is decreased and its duration is increased. A sharp linear drop followed by pulse front is smoothing. Pulse profile is developed to a stepwise waveform. Further a smooth maximum is appeared, a time shift between this maximum and shock front is grown with increasing of layer thickness. A shock structure of a pulse front is destroyed. These effects become more pronounced for the relation $\mathbf{T_0 / 2\pi\tau_{rd} \approx 1}$ ($\mathbf{T_0}$ — is a pulse duration). A comparison of pulse profiles calculated for values of relaxation time 155 ns and 110 ns indicates that in the first case pulse has a shock front after passing through a layer of 2.5 cm thickness, whereas in the second case (Fig. 1b) the shock front is already destroyed after a distance of 2 cm.

Nonlinear effects are especially pronounced if nonlinear length $\mathbf{x_n}$ is less then the distance which pulse passes in a relaxing medium without noticeable attenuation. The value of nonlinear length $\mathbf{x_n}$ depends on pulse duration and its amplitude. For parameters mentioned above this value can be evaluated as $\mathbf{x_n = \rho_0 c_0^3 T_0 / \varepsilon p_0 \approx 2cm}$.

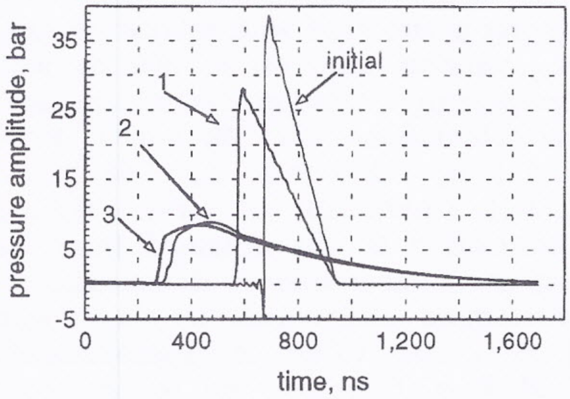

Figure 3 Calculated pulse profiles after passing of 2.5 cm layer of acetic acid. $\tau_{rd} = \mathbf{190ns}$. 1— pulse distortion when nonlinear effects dominate over others. 2— pulse distortion due to relaxation mechanism only. 3— pulse distortion then nonlinearity and relaxation are taken into account.

In nonlinear medium without relaxation the duration of initially triangular pulse is increased and its peak amplitude is decreased even the thermo—viscous energy dissipation is negligible. The profile of pulse is remained as a triangular (Fig.3, curve 1). A simultaneous action of nonlinear and relaxation effects result in additional pulse duration increase (curve 3). Shock front remains its structure at more extended lengths.

EXPERIMENTS

In order to verify the results of numerical calculations a model experiment has been conducted. Short acoustic pulses were exited by a pulse Nd—glass laser radiating 30 ns 4—J pulses at wavelength of 1.06 μm. Light pulse was directed on the layer of light—absorbing liquid. This resulted in fast heating of thin surface layer. Thermal expansion of this heated layer gave rise to generation of a short pressure pulse. Its profile is shown in Fig.2 (curve 3). Pulse duration was about 100 ns and peak pressure reached 100 bar. This pulse then propagated in water and shock front was developed owing to nonlinearity of water (Fig.2). An acoustic pulse with a shock front propagated through a cell with strong acetic acid. The cells of different lengths were used. At the output of the acetic acid layer PVDF membrane hydrophone was placed. Its signal was recorded by digital oscilloscope..

Figure 4 shows pulse profiles after passing through the layer of acetic acid of 2.5 cm thickness. Value of relaxation time of acetic acid decreases with temperature increasing. Data shown at Fig.4a,b,c correspond to 17, 21 and 26 degrees Celsius. Theoretical waveforms were calculated for the various values of relaxation time and a comparison with recorded experimentally profiles was performed. The values of relaxation time were determined from the best profiles matching. Our measurements provided the values of 190 ns, 155 ns and 110 ns at 17, 21 and 26 degrees Celsius correspondingly.

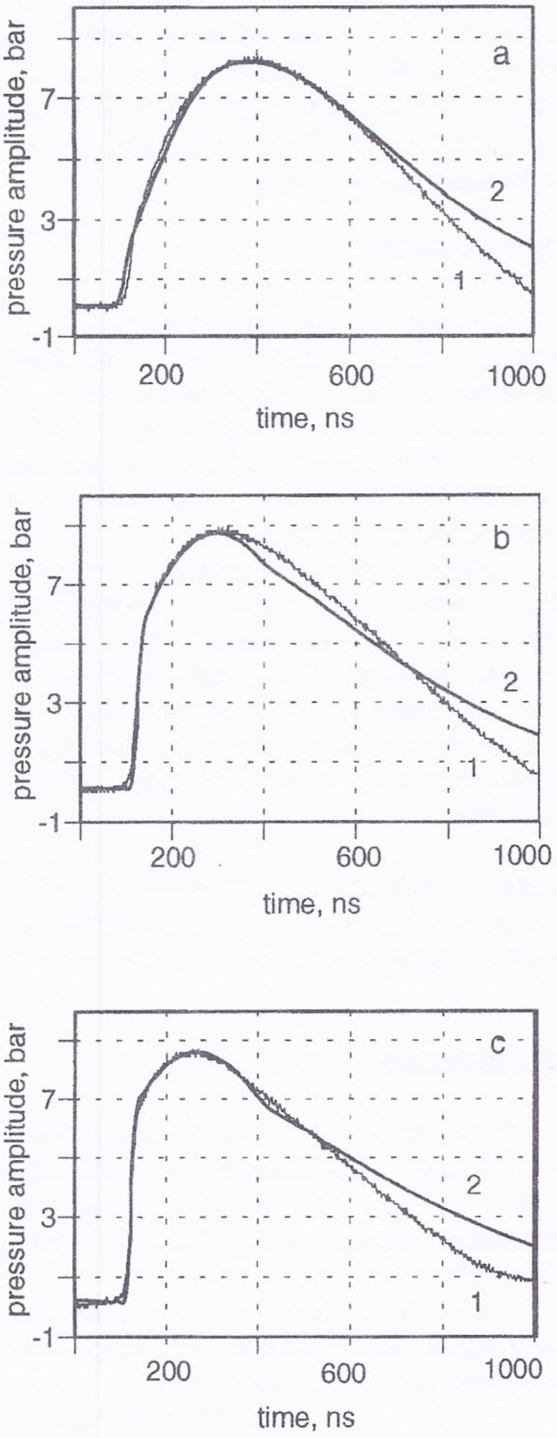

Figure 4. A comparison of experimental and calculated pulse profiles at the entrance of acetic acid layer of 2.5 cm thickness. a) — $\tau_{rel}=110$ ns, b) — $\tau_{rel}=155$ ns, c) — $\tau_{rel}=190$ ns.

However, these values differ from the results described in Bergman,L [5] and Davidovich L.A. and etc. [6] Their values for 20 degree Celsius are 280 and 220 ns correspondingly. This question is of our further investigation

CONCLUSION

Shock wave propagation in relaxing fluid has been studied theoretically and experimentally. It was shown that theoretical model based on nonlinear evolution equation provides an adequate description of shock pulse propagation.

Experimental pulse profiles fitted well to those calculated numerically. It is shown that high accurate values of relaxation time of acetic acid at various temperatures can be determined from the best matching of experimental and theoretical pulse waveforms.

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