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Increase in the Efficiency of the Shear Wave Generation in Gelatin Due to the Nonlinear Absorption of a Focused Ultrasonic Beam

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Abstract—Experimental results and theoretical estimates are presented to demonstrate the prospects of using the acoustic nonlinearity of a gel-like medium for increasing the efficiency of the shear wave generation in it by a pulsed ultrasonic beam. The experiment is based on the propagation of a focused beam of longitudinal acoustic waves at a frequency of 1.1 MHz in a gelatin sample and on the detection of shear waves by the optical method [1]. It is demonstrated that the amplitude of the shear wave excited by a nonlinear acoustic pulse can be increased by an order of magnitude owing to the formation of shock fronts in the profile of this pulse. *© 2002 MAIK "Nauka/Interperiodica".*

An ultrasonic wave that experiences both absorption and scattering in the course of its propagation transfers part of its momentum to the medium. As a consequence, an amplitude-modulated wave produces low-frequency (medium) elastic stresses in the medium, i.e., the radiation pressure [2]. In the case of the ultrasound localization in the form of a beam, the corresponding shear stresses produce a transverse wave propagating in the direction perpendicular to the beam axis (Fig. 1). In common solids, this effect is minor; however, it can become noticeable in gel-like media, where the shear modulus is small and the corresponding shear strain is relatively large. Such media are rubbers, gels, and soft biological tissues. The detection of the amplitude or the propagation velocity of the transverse disturbances provides an opportunity to measure the shear modulus of the medium [1]. This method can be promising for medical applications, e.g., for an early detection of cancer, since the values of the shear moduli for healthy and cancer-affected tissues differ by orders of magnitude [3]. If a focused acoustic beam is used, an efficient generation of shear waves occurs only in the focal region. Thus, it is possible to obtain a local excitation of shear waves in a medium at a large distance from the source of radiation.

The main difficulty in the utilization of this effect is connected with the fact that the excited shear waves are usually very weak, and, therefore, difficult to detect. Hence, it is important to find ways to increase the efficiency of the generation of shear stresses. Here we suggest one such method namely, to use large-amplitude focused ultrasonic pulses whose profiles are nonlinearly distorted in the course of their propagation for increasing the efficiency of the generation of shear-wave signals. Experiments on samples made of gelatin with different concentration (i.e., with different values of the shear modulus) are described. It is demonstrated that, in the case of a constant total energy of the acoustic pulse, it is possible to obtain an amplification of the shear wave by reducing the duration of the excitation pulse and by simultaneously increasing its amplitude to the values at which shock fronts are formed in the wave profile. A theoretical calculation is conducted to compare the efficiencies of the shear wave excitation with and without allowance for the medium nonlinearity and to evaluate the gain.

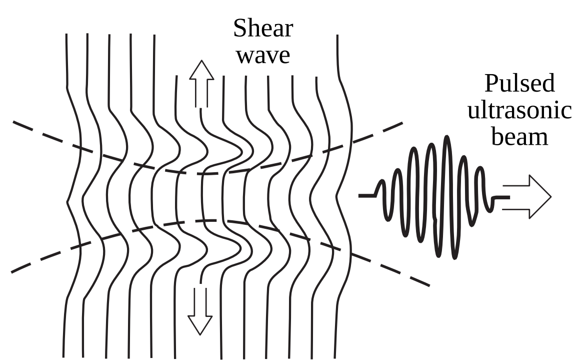

Fig. 1. Excitation of a shear wave due to the absorption of a focused ultrasonic pulse. The dashed lines indicate the boundaries of the ultrasonic beam. The solid lines illustrate the deformation of the medium: in the initial unperturbed state, they formed a family of equidistant vertical straight lines. The absorbed ultrasonic pulse exerts a radiation pressure on the medium, and the shear stress arising in this case produces a quasi-cylindrical shear wave traveling away from the beam axis.

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The setup used in the experiments is schematically represented in Fig. 2. An ultrasonic beam was produced by a focusing piezoceramic transducer 10 cm in diameter with a 20-cm curvature radius. The transducer operated at a resonance frequency of 1.1 MHz [4]. The longitudinal and transverse dimensions of the focal region, which were measured according to the zeros of the amplitude distribution of the pressure field, were 87 and 7 mm, respectively. The transducer was excited by an electric signal from an HP33120A generator using an ENI AP400B power amplifier. We used a pulsed regime of excitation with rectangular envelopes of pulses. The pulse duration varied from 40 to 700 μs. The source was submerged into a water basin with the dimensions $20 \times 20 \times 60$ cm^3 and could be moved with the help of a positioning system (Velmex VP9000, USA) in three mutually perpendicular directions. A gelatin sample shaped as a cylinder with a diameter of 80 mm and a generatrix of 65 mm was placed into the focal region of the ultrasonic beam. Figure 3 shows a photograph of the ultrasonic transducer (on the left) and one of the samples (on the right). The sample was positioned in such a way that the cylinder axis coincided with the acoustic axis and the central section of the cylinder lay in the focal plane of the source. An optical system described in [1] was selected to detect the shear waves. The beam of a helium-neon laser was focused at the edge of an opaque particle 60–300 μm in size, which was placed in the medium. On the shear wave arrival, the particle moved and modulated the transmitted energy of the laser beam. The light signal detected further by a photodiode was proportional to the shear displacement. To incorporate such modulator particles into the medium, gelatin samples were manufactured in two stages, which provided an opportunity to put the particles into the central section perpendicular to the cylinder axis.

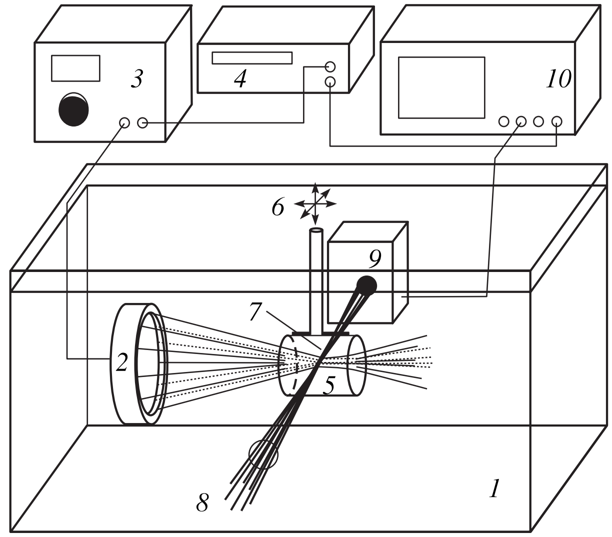

Fig. 2. Experimental setup: (*1*) a water basin, (*2*) an ultrasonic transducer, (*3*) an electric power amplifier, (*4*) a generator, (*5*) a gelatin sample, (*6*) a micropositioning system, (*7*) a shutter particle, (*8*) a beam of a He-Ne laser, (*9*) a photodiode, and (*10*) a digital oscilloscope.

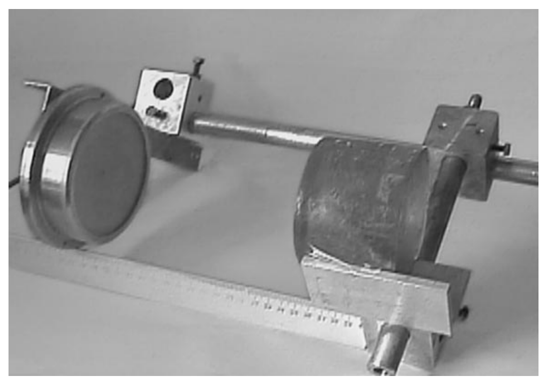

Fig. 3. Photograph of the piezoceramic transducer (on the left) and the gelatin sample (on the right).

The purpose of our measurements was to demonstrate that the use of an acoustic wave with shocks in its profile makes the excitation of shear-wave signals much more efficient. Ultrasonic pulses with different amplitudes, but with the same energy (which was attained by the corresponding choice of the pulse duration) were used. If the ultrasonic propagation in the medium were linear, the amplitude of the shear waves excited by acoustic pulses with the same energy would be the same [1]. However, in the presence of nonlinearity, the profile of an ultrasonic wave in the focal region of the beam becomes distorted, and in the case of a rather large amplitude, shock fronts arise, i.e., a sawtooth profile is formed. As a consequence, the wave is absorbed more efficiently and transfers a greater part of its momentum to the medium, as compared to the case of linear propagation. Thus in the nonlinear regime, one can expect a considerable increase in the amplitude of the shear disturbance generated by the ultrasonic wave.

The regime calibration according to the total energy of acoustic pulses was performed by measuring the average radiation force exerted by a periodic sequence of pulses on a wide-aperture target absorber [5]. The target was shaped as a cylinder 12 cm in diameter and 5 cm in height and was made of rubber of the type of an RTV-2 two-component silicon elastomer, which had a large absorption coefficient and an acoustic impedance close to the impedance of water. To measure the radiation force, an acoustic beam was directed to the absorber from below and the absorber was weighted both under the ultrasonic irradiation and immediately after switching off the source of ultrasound [6]. In such measurements, the change in the absorber weight ΔP and the average ultrasonic power W are related as $\Delta P/W = 67$ mg/W [5]. On the basis of these measurements, several regimes of operation with different lengths and amplitudes of pulses were selected for a preset acoustic energy.