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ULTRASONIC LASER SPECTROSCOPY OF MECHANIC-ACOUSTIC NONLINEARITY OF CRACKED ROCKS

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The effect of nonlinearity of rocks caused by the presence of microcracks on the shape of elastic pulses propagating in these rocks is studied by methods of ultrasonic laser spectroscopy.

Key words: *ultrasonic laser diagnostics, microcracked geomaterials, structural inhomogeneities.*

Introduction. Microfracturing is an important characteristic of geomaterials, responsible for their cube strength, frost resistance, abradability, elastic and other properties including technological properties, which substantially affect the processes of failure and concentration [1]. Moreover, microfracturing plays an important role in preparing macrofracture of rocks and dangerous dynamic phenomena in them [2]; hence, it must be taken into account in predicting and monitoring these processes. At present, it is common practice to estimate microfracturing by the method of microstructural analysis of metallographic sections, which allows obtaining crack parameters by means of their direct microscope visualization. To obtain an adequate estimate of microfracturing parameters of rocks on the basis of specimens, however, one has to apply a statistical approach based on averaging data obtained on a large number of metallographic sections whose preparation is an extremely labor-consuming procedure.

The less common method is based on the capillary impregnation of specimens with a liquid luminiscent under ultraviolet radiation and subsequent microscopic analysis [3]. Using this method, one obtains the desired information only from the surface of the objects studied but cannot infer the distribution of microcracks over the specimen depth.

In view of the difficulties mentioned above, ultrasonic methods of travelling waves, in which the propagation velocity of elastic oscillations is used as an informative parameter [4], should be considered as an effective tool for studying the integral characteristics of microcracks. However, this velocity is relatively little affected by the presence of microcracks (to several percent). Moreover, it depends substantially on a number of factors (mineral-grain size and orientation, various inclusions, contact conditions, etc.), which do not allow unambiguous identification of the contribution of microcracks into velocity variation.

In this connection, much attention has been given recently to development of noise-immune methods of geomaterial defectoscopy, based on nonlinear effects typical of high-power ultrasonic signals propagating over cracked media. These effects include generation of higher harmonics, occurrence of combination frequencies, nonlinear ultrasonic attenuation, resonant frequency shift, etc. [5–10].

Recent theoretical studies showed [11–13] that nonlinearity can have other effects, which can be used to increase the sensitivity in determining microcrack characteristics. Within the framework of hysteretic models, nonlinearity was demonstrated to substantially change the shape of elastic-wave pulses. However, no experimental results on nonlinear distortion of time profiles have been reported so far. The main reason is that no technical means existed for generation of high-power broad-band pulses in a geomedium until recently. In the present paper, the effect of microcracks in rock specimens on nonlinear distortion of the pulse shape is studied experimentally by methods of ultrasonic laser inspection of the structure.

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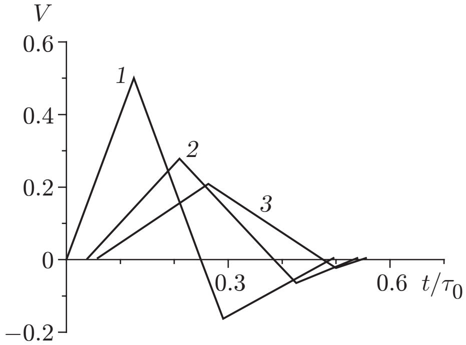

Fig. 1. Distortion of a triangular pulse for different values of the nonlinear parameter ζ: curve 1 refers to $\zeta = 0$ (input signal) and curves 2 and 3 refer to $\zeta = 0.5$ and 5/3, respectively.

Theoretical Models. Theoretical investigations of the processes of nonlinear propagation and interaction of acoustic waves in various solid media were usually performed on the basis of the classical five- or nine-constant theory of elasticity [14]. For longitudinal stresses σ and strains ε, the Taylor series expansion $\sigma(\varepsilon)$ in the quadratic and cubic approximations, respectively, is considered as the equation of state. When a harmonic signal propagates through this medium, higher harmonics are generated, whereas a shock front is formed upon propagation of a pulsed signal.

This approach cannot be applied to describe inhomogeneous media such as rocks. In view of their complex structure and the presence of cracks, grains, voids, etc., it is necessary to use a more intricate equation of state.

In acoustics and seismoacoustics [7], equations of state containing hysteretic nonlinearity are increasingly used to describe nonlinear wave processes in various microinhomogeneous media. In [5–9], hysteresis equations of state with quadratic and cubic nonlinearities were constructed by analyzing experimental amplitude dependences of nonlinear losses, the shift of resonance frequencies, and the levels of higher harmonics in resonators made of metals and rocks (granite and marble). On the basis of these equations, nonlinear wave processes in an unconfined medium and in a rod resonator were studied by the perturbation method. Parameters of the hysteretic nonlinearity of these media were determined by comparing analytical calculations and experimental results.

In a series of theoretical and experimental studies whose basic results are reviewed in [10], hysteretic dependences were obtained by numerical simulations of the behavior of a medium containing an ensemble of the Preisach–Mayergoyz elements [15]. The hysteresis obtained in this manner was used to study nonlinear distortion of an initially harmonic wave. As a result, the values of effective parameters of the nonlinearity were obtained for sandstone, limestone, and concrete. In [11–13], this hysteresis is described analytically (in the quadratic approximation) and the propagation and interaction of initially harmonic waves and triangular pulses are studied theoretically.

As is predicted by these models, an asymmetric triangular bipolar pulse (curve 1 in Fig. 1) is transformed as follows [13]. The duration of each phase increases and the relation between their amplitudes changes (see curves 2 and 3 in Fig. 1) with the distance the pulse traverses in the hysteretic medium. The rarefaction phase is entirely absorbed at certain distances. Figure 1 shows the nonlinear distortion of asymmetric bipolar pulses for different values of the parameter $\zeta = x/x_{nl}$, where x is the distance traversed by the wave in the medium, $x_{nl} = 2c_0^2\tau_0/(hV_0)$ is the nonlinear parameter, c_0 is the propagation velocity of longitudinal waves, τ_0 is the initial duration of the pulse, V_0 is the amplitude of the fluctuating velocity of particles, and h is the width of the hysteresis loop.

For highly cracked media, a bipolar pulse is transformed in a different way: the propagation velocities of the compression and rarefaction phases of the bipolar pulse differ, which results in their separation in time.

Experimental Investigations. Cubic specimens of Karelian gabbro with a side of about 3 cm were studied. Their ultimate strength under uniaxial compression was approximately 300 MPa. Two groups of specimens were considered. The first group consisted of specimens with longitudinal cracks. They were localized in advance by ultrasonic laser echoscopy [16]. The surfaces of the specimens were scanned and, after computer processing of signals, an image of the plane section where a crack was located was obtained. The second group consisted of

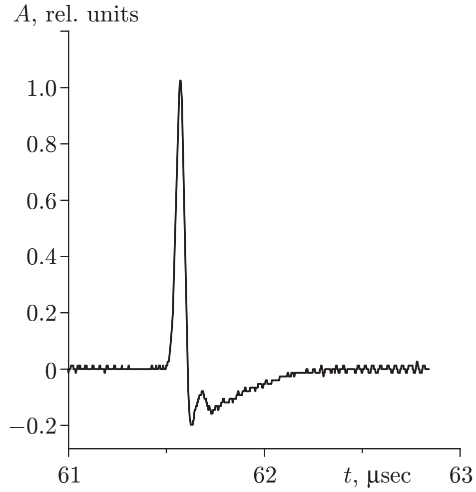

Fig. 2

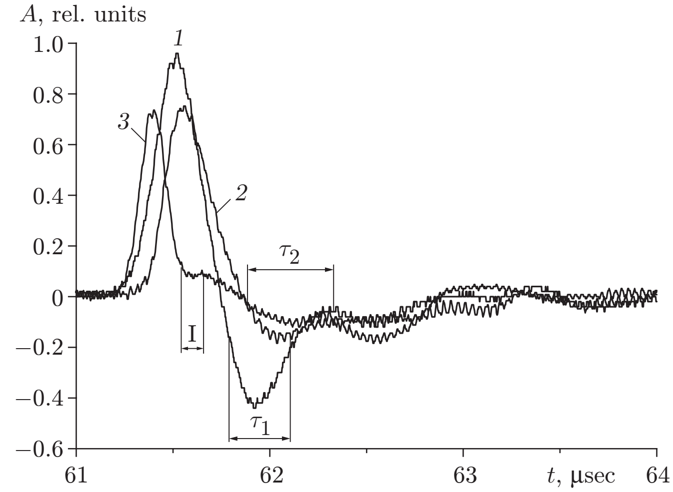

Fig. 3

Fig. 2. Shape of the reference acoustic pulse passed through a dish filled by distilled water.

Fig. 3. Shapes of acoustic pulses passed through a Karelian-gabbro specimen: 1) through the crack-free region; 2) near the crack; 3) through the crack.

specimens without cracks. The frequency dependences of the propagation velocity of longitudinal elastic waves and their attenuation coefficient measured in the frequency range of 1–3.5 MHz showed that these specimens were also isotropic.

To study the nonlinear transformation of acoustic pulses propagating in the rock specimens of both groups, a "GEOSCAN-02M" setup described in [17] was used. The source of optical pulses in this setup is a solid-state laser operating at the wavelength $\lambda = 1.06$ μm. The laser-pulse duration was $\tau_0 = 10$ nsec, and the maximum value of energy was 260 mJ. The energy could be reduced to 20 mJ using light filters. The beam radius was 5 mm. A laser pulse absorbed in the generator (which was a high-pressure polyethylene film) excited pulses of longitudinal elastic waves with a duration of 100 nsec and amplitude pressure up to 10 MPa. To measure the parameters of acoustic signals after their propagation through the specimen, the immersion method was employed: the examined specimens were immersed into distilled water. Signals that passed through the medium were recorded by a broad-band piezoelectric film detector. The latter was connected via a preamplifier to a Textronix TDS-220 digital storage oscilloscope (with an analog frequency of 100 MHz and a discretization frequency of 1 GHz) whose signal was analyzed on a computer. The time resolution of the recording system was 3–4 nsec, and the signal-to-noise ratio was 30 dB.

Ultrasonic irradiation of various regions of the first-group specimens was performed using the equipment described above. Results are given for one of the most typical specimens. Initially, the regions without cracks were studied.

Figure 2 shows the reference pulse after its propagation through a dish filled by distilled water. This pulse displays compression and rarefaction phases with an amplitude ratio of 5 : 1. The spectrum of this pulse extends up to 10 MHz. As this pulse propagates through the region without cracks, diffraction and dissipation on specimen inhomogeneities lead to a decrease in the compression-phase amplitude and to a substantial increase in the rarefaction-phase amplitude, as compared to the compression phase (curve 1 in Fig. 3; the amplitude ratio of these phases becomes equal to 2.5 : 1). Moreover, the pulse duration increases threefold as a result of dissipation of the high-frequency part of the spectrum; frequencies below 3 MHz remain in the spectrum. Since the crack localization was known, the second region of sounding was chosen so that the ultrasonic beam was partly incident on the crack origin. In this case, nonlinear transformation of the pulse shape occurred (curve 2 in Fig. 3). This transformation was primarily manifested in an abrupt decrease in the amplitude of the rarefaction phase (by a factor of 2.7) and an increase in its duration τ from the initial value $\tau_1 = 0.348$ μsec in the signal that passed through the crack-free region to $\tau_2 = 0.446$ μsec. In the process, the amplitude of the compression phase decreased only by a factor of

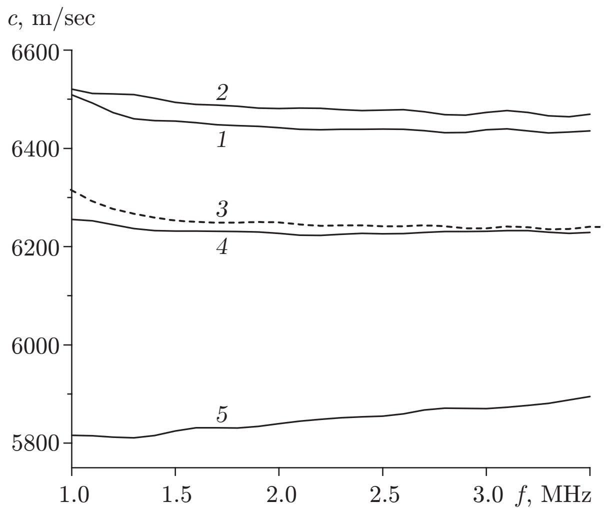

Fig. 4

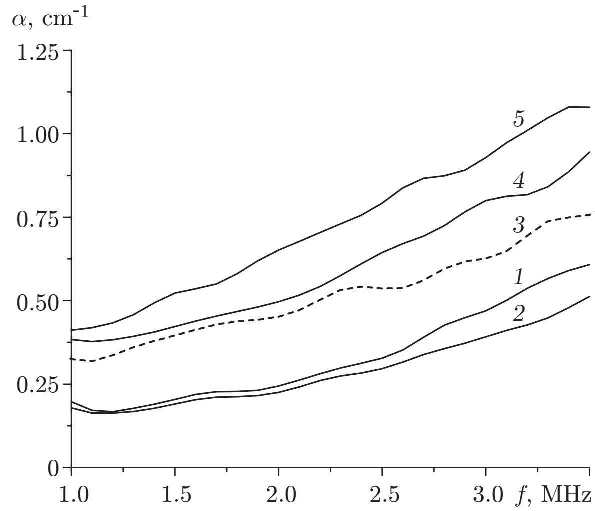

Fig. 5

Fig. 4. Frequency dependence of the propagation velocity of longitudinal waves in the loading direction in a Karelian-gabbro specimen after applying the load $\sigma = 34$ (1), 68 (2), 112 (3), 253 (4), and 280 MPa (5).

Fig. 5. Frequency dependence of the attenuation coefficient of longitudinal waves in the loading direction in a Karelian-gabbro specimen after applying the load $\sigma = 34$ (1), 68 (2), 112 (3), 253 (4), and 280 MPa (5).

1.5, and its duration remained almost unchanged, as compared to the signal that passed through the intact part of the specimen. If the reference signal propagated directly through the middle of the crack, two phases of the bipolar pulse (curve 3 in Fig. 3) were observed to separate in time against a background of an abrupt decrease in the rarefaction-phase amplitude. The presence of the horizontal part I in the acoustic signal supports the fact that the compression and rarefaction phases propagate with different velocities.

In the second series of measurements, the influence of defects produced by specimen loading on the shape, propagation velocity, and attenuation coefficients of elastic-wave pulses was studied. For this purpose, initially crack-free isotropic Karelian-gabbro specimens were used. All specimens were subjected to a cyclic uniaxial load σ; when the load was removed, measurements were performed in the loading direction. The maximum stresses were 34, 68, 112, 253, and 280 MPa for each of five loading cycles, respectively. Further loading of the specimen to 295 MPa led to its failure.

Initially, the frequency dependences of the attenuation coefficient and propagation velocity of longitudinal elastic waves were determined within the range $f = 1$–3.5 MHz for a specimen preloaded to 34 MPa. The corresponding dependences are plotted in Figs. 4 and 5 (curves 1). In the specimen preloaded to 68 MPa, the ultrasonic velocity was found to increase by 1% (curve 2 in Fig. 4), which was caused by its compaction in the sounding direction. In this case, as can be seen from Fig. 4, velocity dispersion is insignificant within the entire frequency range considered. The above-mentioned increase in velocity can also be recognized on the basis of a 0.15 μsec decrease in the duration of pulse propagation over the specimen (curve 2 in Fig. 6).

The attenuation coefficient, which decreases by 17% as the load increases from 34 to 68 MPa for a frequency of 3 MHz (curves 1 and 2 in Fig. 5) turns out to be the most sensitive parameter to specimen compaction. Under the load $\sigma = 112$ MPa, acoustic emission substantially increases, and cracks defining sharply the grain contours appear at the specimen surface. The measurements show that the velocity (curve 3 in Fig. 4) decreases by 3% and the attenuation coefficient (curve 3 in Fig. 5) increases by 32% at a frequency of 3 MHz, as compared to the initial value (curves 1). In this case, the shapes of pulses after propagation through loaded specimens are transformed as follows. As in the previous case, the reference signal consists mainly of the compression phase (see Fig. 2). In the acoustic signal (curve 1 in Fig. 6) that passed through the specimen preloaded to $\sigma = 34$ MPa, the ratio of the amplitudes of the phases becomes equal to 1.5 : 1, i.e., the rarefaction-phase amplitude significantly increases owing to diffraction and dissipation. After applying loads lower than 112 MPa, no substantial distortions in the pulse

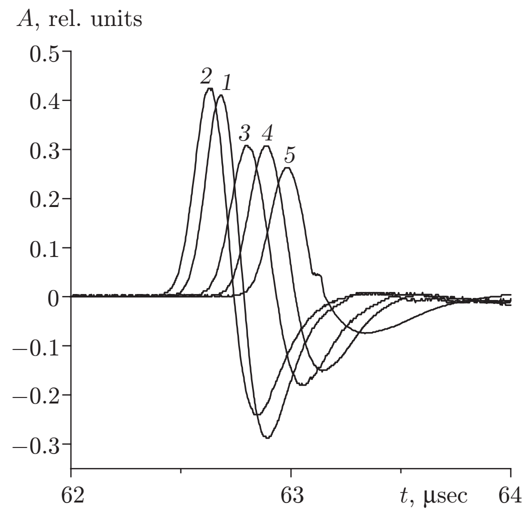

Fig. 6. Shapes of acoustic signals passed through a Karelian-gabbro specimen in the loading direction after applying the load $\sigma = 34$ (1), 68 (2), 112 (3), 253 (4), and 280 MPa (5).

shape are observed (curve 2 in Fig. 6). Initiation of microcracks (for $\sigma = 112$ MPa) leads to a substantial decrease in the rarefaction-phase amplitude (curve 3 in Fig. 6). As the uniaxial loading increases to 253 MPa, the number of microcracks increases and, correspondingly, the rarefaction phase decreased. The ratio of the amplitudes of the two phases of the bipolar pulse is 2 : 1. Under the load $\sigma = 280$ MPa, a macrocrack with a length of more than 2 cm appears. As a result of propagation of an acoustic signal through this crack, two phases of the bipolar pulse are observed to separate in time with a further decrease in the rarefaction-phase amplitude and an increase in its duration (curve 5 in Fig. 6). In the process, the propagation velocity of longitudinal waves decreases (curve 5 in Fig. 4) and the attenuation coefficient increases (curve 5 in Fig. 5) within the entire frequency range considered. Under the load $\sigma = 295$ MPa, the specimen fails.

Conclusions. Testing of Karelian-gabbro specimens shows that their nonlinearity is manifested as a distortion of the shape of a short pulse of elastic longitudinal waves propagating through these specimens. For a small number of microcracks, according to the theoretical estimates given in [11, 13], nonlinear transformation of pulsed signals is manifested in an unchanged shape of the compression phase and in a decrease in the rarefaction-phase amplitude. In the presence of a crack with an opening depth of $\approx$100 μm or greater, the nonlinear distortion is responsible for a difference in propagation velocities of the compression and rarefaction phases, i.e., these two phases are separated in time. This possibility was studied theoretically in [12].

In summary, a nonlinear transformation of the shape of ultrasonic sounding signals can be considered as an effective tool for revealing and estimating parameters of microcracks in rock specimens.

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