Laser-ultrasonic spectroscopy for geological testing and the description of laser ultrasonic setup “GEOSCAN-02M” are presented. The measurements of acoustical characteristics of rocks (for example, attenuation, sound velocity) and the investigations of mechanic-acoustic nonlinearity of cracked rocks are carried out by “GEOSCAN-02M”.

Introduction

Ultrasound methods make it possible to solve a great number of geo-testing problems, including description of elastic and strength properties of geo-materials, estimation of their structural non-uniformity, imperfection, anisotropy and others. At the same time, practical application of ultrasound methods shows that their significant potentials are not being fully realized. This is connected, first of all, with imperfection of appropriate apparatus, which does not allow to make ultrasound measurements over a wide frequency range and combine obtaining integral estimates of the parameters with a high space-time resolution. This problem can be solved by using laser ultrasound spectroscopy. Basic principles and examples of practical application of this method will be considered below.

1 Laser-ultrasonic setup “GEOSCAN-02M”

The “GEOSCAN-02M” setup principle of work is based on thermo optical excitation of short powerful ultrasonic pulses [1] and spectrum analysis of the signals passed though investigated environment. Distinctive feature of the system is widebandness of the examinations taking place on it, which allows to get dispersion dependences of attenuation and velocity of ultrasound over the frequency range 0.1 - 45 MHz. The block-scheme is presented on Figure 1.

![Figure 1: The block-scheme of laser ultrasonic setup “GEOSCAN-02M”](image)

The laser pulse source is solid Q-switch pulse laser 3. The maximal pulse energy is 260 mJ, pulse duration – 10 ns. The optical beam falls initially on the light diffuser 4, which served for uniform on a cross-section intensity distribution formation. After that the laser pulse energy is varied by light filter system 5. After that the light pulse falls on low-frequency 1 or high-frequency 2 optical-acoustic cells. The low-frequency cell is cuvette in which the immersion fluid (was usually used distilled water) was flooded. The generator 6 of ultrasonic pulses was immersed in it. As the generator the high-pressure polyethylene film was used, which ultrasonic impedance was close to an ultrasonic impedance of an immersion fluid. Therefore as a result of absorption in the film of laser pulse and its subsequent expansion the uni directional pulse of pressure was excited, which forward front duration made 50 ns that matched to working frequency band from 100 kHz up to 12 MHz, pressure amplitude – 10 MPa, the working aperture – up to 20 mm. The signals were recorded by damper piezo-receiver 7, which based on PVDF film with thickness 110 $\mu$m. This receiver is combined with preamplifier, and the working frequency band of reception duct made 0.3-8 MHz. At the same time the diameter of the receptions aperture made 53 mm. The detection threshold of the wideband piezoelectric element in no-load conditions was defined by the noise charge of its capacity and made 5 Pa. Therefore the dynamic range of given part of setup was equal 60 dB.

The sample positioned in the cuvette in the special clamp device 8, allowing to twirl it around of an axis of yaw. The signal from the piezo-receiver comes to digital storage oscillograph 9. As the laser worked in a pulse periodic mode averaging on 128 realizations was carried out that allowed to increase the signal-to-noise merit, at least, on the order. The average signal moved on a computer 10. With the help of the “Matlab” software package and using fast Fourier-transformation, was calculated amplitude spectrum of signals (the attenuation coefficient in given frequency range calculate by it) and the phase spectrum on which
it was investigated, accordingly, sound velocity dispersion.

The second part of setup worked or as a high-frequency cell 2, or served for diagnostic of geomaterial samples of the small sizes when excitation of ultrasound occurs as a result of the laser radiation absorption immediately on the sample surface. In the case in a sample there are pulses both longitudinal and shear waves, and on a delay time of given pulses relative to laser it is possible to calculate the propagation velocities of the longitudinal and shear waves, carrying out measurements for sample thickness down to 3 mm. In the high-frequency cell 2 the light filter SZS-22 was picked as standard generator 11. In this case at the free boundary there is a bidirectional pulse with forward front duration of 50 ns and spectral range 2-45 MHz. The working generator aperture attains 30 mm. The piezo-receiver 12 is produced from lithium niobate crystal, thickness is equal 7 mm, that matched to spectral range 2-100 MHz. The second cell is more convenient for using for porous environments, when the immersion method is inapplicable. On setup “GEOSCAN-02M” the examinations can be carried out in the transmitted waves mode.

2 The measurements of rocks acoustical characteristics on samples of the small sizes

The marble, limestone and ferruginous quartzite samples were studied. Initially the samples of marble and limestone represented cubes with the edge \( h=30 \text{ mm} \). Such sample sizes allowed to measure the velocities of longitudinal and shear waves by the standard defectoscope. The values obtained thus for velocities are given in table 1.

Initially the same cubes were studied by the laser ultrasonic setup “GEOSCAN-02M” and then they have been cut on plates by thickness 6-8 mm, which again were exposed to laser action. Since the ultrasonic beam width in standard defectoscope made some centimeters, the wide laser beam was used for opportunity of experimental data comparison. As result of light beam absorption on the surface of plates all elastic wave types were excited: the surface, longitudinal and shear.

Use of laser radiation for excitation of elastic wave pulses give one more advantage. If the standard defectoscope with wide beam allows to measure elastic wave velocity values only average by volume, the optical beam focusing gives opportunity of measurements of local value of velocity. The carried out scanning on sample surface with the step of 5 mm has shown, that the longitudinal and shear wave velocity values varied in limits of 10%.

<table>
<thead>
<tr>
<th>Rock type and sample thickness</th>
<th>The measured values of ultrasonic velocities ( ( c_l ) - longitudinal wave, ( c_s ) - shear wave), km/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard defectoscope</td>
</tr>
<tr>
<td>Marble, ( h=30 \text{ mm} )</td>
<td>( 4.9, 2.81 )</td>
</tr>
<tr>
<td>Marble, ( h=8 \text{ mm} )</td>
<td>- -</td>
</tr>
<tr>
<td>Limestone, ( h=30 \text{ mm} )</td>
<td>( 4.63, 2.43 )</td>
</tr>
<tr>
<td>Limestone, ( h=8 \text{ mm} )</td>
<td>- -</td>
</tr>
</tbody>
</table>

As well the series of ferruginous quartzite samples from Michaylovskoe deposit were studied. The sound velocity estimations at scanning on surface with step of 5 mm are given in table 2 for two the most typical samples.

<table>
<thead>
<tr>
<th>The samples of ferruginous quartzite</th>
<th>The longitudinal wave velocity, km/s</th>
<th>The shear wave velocity, km/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( c_l^\text{max} )</td>
<td>( c_l^\text{min} )</td>
</tr>
<tr>
<td>№1</td>
<td>5.68</td>
<td>5.21</td>
</tr>
<tr>
<td>№2</td>
<td>6.32</td>
<td>5.93</td>
</tr>
</tbody>
</table>

The following basic minerals entered into a composition first from them: magnetite, quartz, calcite, green mica, and hydroxides. The sample №1 with thickness of 4.6 mm has been taken from depth of 73 m. From table 2 it is visible, that mean of elastic waves velocities for the given sample has made accordingly: 5.35 \( \cdot \) km/s - for longitudinal waves and 2.77 \( \cdot \) km/s - for shear.

The second sample differed from first on a mineral composition. At it instead of mica was present aegirite. The sample has been taken from depth of 271 m and its thickness was equal 4.5 mm. The mean of elastic waves velocities received for it has made: 6.08 \( \cdot \) km/s for longitudinal waves and 3.24 \( \cdot \) km/s - for shear.
Difference in a mineral composition, and also various stratification depth, have resulted in difference in sound velocity values. To carry out measurements on the given samples by the standard defectoscope did not appear possible.

3 Investigation of mechanic-acoustic nonlinearity of cracked rocks.

3.1 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 [2]. For longitudinal stresses $\sigma$ and strains $\varepsilon$, 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.

![Figure 2: Distortion of a triangular pulse for different values of the nonlinear parameter $\zeta$](image)

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 [3], equations of state containing hysteretic nonlinearity are increasingly used to describe nonlinear wave processes in various microinhomogeneous media. In [3-7], 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 [8], hysteretic dependences were obtained by numerical simulations of the behavior of a medium containing an ensemble of the Preisach-Mayergoyz elements [9]. 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 [10-12], 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 Figure 2) is transformed as follows [12]. The duration of each phase increases and the relation between their amplitudes changes (see curves 2 and 3 in Figure 2) with the distance the pulse traverses in the hysteretic medium. The rarefaction phase is entirely absorbed at certain distances. Figure 2 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\tau_0 / h
$ is the nonlinear parameter, $c_0$ is the propagation velocity of longitudinal waves, $\tau_0$ 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.

3.2 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 [13]. 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
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.

Figure 3: Shape of the reference acoustic pulse passed through a dish filled by distilled water.

Figure 4: Shapes of acoustic pulses passed through a Karelian-gabbro specimen: 1) through the crack-free region; 2) near the crack; 3) through the crack.

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

Figure 3 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 Figure 4; 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 Figure 4). 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 $\tau$ from the initial value $\tau_1 = 0.348 \mu s$ in the signal that passed through the crack-free region to $\tau_2 = 0.446 \mu s$. In the process, the amplitude of the compression phase decreased only by a factor of 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 Figure 4) were observed to separate in time against a background of an abrupt decrease in the rarefaction-phase amplitude. The presence of the horizontal part 1 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; 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 Pa.

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 Figure 5), which was caused by its compaction in the sounding direction. In this case, as can be seen from Figure 5, 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 $\mu$sec decrease in the duration of pulse propagation over the specimen (curve 2 in Figure 7).

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 Figure 6) turns out to be the most sensitive parameter to specimen compaction. Under the load $\sigma = 112$ MPa, acoustic emission
Figure 5: 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).

Figure 6: 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).

substantially increases, and cracks defining sharply the grain contours appear at the specimen surface. The measurements show that the velocity (curve 3 in Figure 5) decreases by 3% and the attenuation coefficient (curve 3 in Figure 6) 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 Figure 2). In the acoustic signal (curve 1 in Figure 7) 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 shape are observed (curve 2 in Figure 7). Initiation of microcracks (for $\alpha = 112$ MPa) leads to a substantial decrease in the rarefaction-phase amplitude (curve 3 in Figure 7). 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.

Figure 7: 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).

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 Figure 7). In the process, the propagation velocity of longitudinal waves decreases (curve 5 in Figure 5) and the attenuation coefficient increases (curve 5 in Figure 6) within the entire frequency range considered. Under the load $\sigma = 295$ MPa, the specimen fails.

Conclusion

The laser ultrasonic setup “GEOSCAN-02M” allows to measurements of rocks acoustic characteristics on the samples of small sizes (thickness down to 3 mm) in contrast to standard defectoscope.

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 [10, 12], 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 $\approx 100 \mu m$ 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 [11].

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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References