

# Nonlinear Transformation of Laser Generated Ultrasonic Pulses in Geomaterials

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**Abstract**—Nonlinear evolution of broadband ultrasonic pulses passed through the rock specimens is studied using the apparatus “GEOSCAN-02M”. Ultrasonic pulses are excited by the pulses of Q-switched Nd:YAG laser with the time duration of 10 ns and with the energy of 260 mJ. This energy can be reduced to 20 mJ by some light filters. The laser beam radius did not exceed 5 mm. As a result of the absorption of the laser pulse in the special material – the optoacoustic generator—the pulses of longitudinal ultrasonic waves are excited with the time duration of 100 ns and with the maximum pressure amplitude of 10 MPa. The immersion technique is used to measure the parameters of these ultrasonic pulses passed through a specimen, the immersion liquid is distilled water. The reference pulse passed through the cell with water has the compression and the rarefaction phases. The amplitude of the rarefaction phase is five times lower than that of the compression phase. The spectral range of the reference pulse reaches 10 MHz. The cubic-shaped specimens of the Karelian gabbro are studied with the rib length 3 cm. The ultimate strength of the specimens by the uniaxial compression is (300±10) MPa. As the reference pulse passes through the area of the specimen without cracks the compression phase decreases and the rarefaction one increases due to diffraction and scattering of ultrasound, so the ratio of these phases becomes 2.3:1. After preloading some horizontal cracks appear in the specimens. Their location is found by one-sided scanning of the specimen using the backward mode detection of the ultrasonic pulses reflected from the structure defects. Using the computer processing of these signals the images are obtained of the cross-sections of the specimens with cracks. By the increase of the reference pulse amplitude from 0.1 MPa to 5 MPa the nonlinear transformation of the ultrasonic pulse passed through the specimen with horizontal cracks results in the decrease by 2.5 times of the amplitude of the rarefaction phase and in the increase of its duration by 2.1 times. By the increase of the reference pulse amplitude from 5 MPa to 10 MPa the time splitting of the phases is observed for the bipolar pulse passed through the specimen. The compression and rarefaction phases propagate with different velocities. These features of the powerful broadband ultrasonic pulses passed through the rock specimens can be described by the hysteresis model of Preisach-Mayergoyz and can be used for the location of cracks in the optically opaque materials.

**Keywords**—Cracks, geological materials, nonlinear evolution of ultrasonic pulses, rock.

## I. INTRODUCTION

THE study of the manifestation of nonlinear physical and mechanical properties of heterogeneous materials is of special interest for nondestructive evaluation purposes. These

properties to a large extent determine the stability and durability of various structures.

The processes of nonlinear propagation and interaction of acoustic waves in homogenous solids are governed by classical lattice nonlinearity [1]. They are normally studied within the classical five- or nine-constant theory of elasticity [2]. As an equation of state for shear stresses  $\sigma$  and deformations  $\varepsilon$  in isotropic media, this theory assumes Taylor's series expansion  $\sigma(\varepsilon)$  for  $\varepsilon$  in quadratic and cubic approximations respectively:

$$\sigma(\varepsilon) = E(\varepsilon - \frac{\gamma}{2}\varepsilon^2 + \dots) \quad (1)$$

where  $E$  is Young's modulus,  $\gamma$  is the quadratic nonlinearity parameter,  $|\gamma| \ll 1$ . When a pulse signal propagates in such a medium, it becomes enriched with harmonics and the shock front is formed.

Such an approach is not applicable for describing heterogeneous media that include rock formations, structural materials and other heterogeneous materials. Their complex structure and presence of cracks, grains and pores necessitate introduction of a more complicated equation of state. Thus, for example, presence of cracks in a solid body may result in its different modularity – i.e. difference in the moduli of elasticity during compression and stretching; granular structure of a material may change the degree of nonlinearity in the equation of state from integer 2 in the five-constant theory of elasticity to fraction 3/2 [3], linear lattice defects – dislocation – result

in the hysteretic (i.e. ambiguous) dependence  $\sigma = \sigma(\varepsilon, \dot{\varepsilon})$  ( $\dot{\varepsilon}$  is the deformation rate) for polycrystals [4]. The effective nonlinearity parameter of micro-inhomogeneous media is 3-4 orders greater than the respective parameter of homogeneous media and materials [5]-[7]. Due to that, the nature of nonlinear effects during propagation and interaction of elastic waves in various micro-inhomogeneous media differs, generally speaking, not only quantitatively, but also qualitatively [8]. This may be used for their diagnostics and nondestructive evaluation. Nonlinear acoustic properties of such media are also more defect-sensitive than linear ones [9], [10].

By now, two major approaches have been developed for describing the process of elastic wave propagation in fractured media. The first one is associated with the research of fractured media for which hysteresis bi-modular model is assumed [11]. In the second case, to study the nonlinear

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propagation of ultrasonic pulses, the Preisach-Mayergoyz model is used, where several nonlinear parameters are introduced [11].

Within the bi-modular theory [12] with one nonlinear parameter defining the hysteresis loop width, an analytical solution was obtained for triangular unipolar and bipolar pulses of longitudinal waves [13]. It was shown that during propagation of non-symmetric triangular pulses in such a medium, along with an increase of duration there is a greater reduction of the rarefaction phase amplitude in a weakly fractured medium as compared to the compression phase. At a certain distance from the source the compression phase becomes equal to zero.

During propagation of bipolar pulses in high-fractured media, the bipolar pulse propagation rates are different for the rarefaction phase and the compression phase. As a result, they are separated in time.

This work deals with the research of nonlinear transformation of optoacoustic pulses when propagating in geomaterials.

## I. METHODS

To observe the nonlinear transformation of acoustic pulses in heterogeneous media, for which the equation of state is determined by the hysteresis curve, it is necessary that the pressure amplitude of such pulses reaches several mega Pascals. In this case the nonlinear interaction of ultrasonic waves with inhomogeneities in the structure of the studied medium will not be masked by diffraction and dissipation on the defects.

The laser sources of ultrasound permit excitation of aperiodic ultrasonic signals of smooth shape taking the spectral range of 3–6 octaves with amplitude of up to 10 MPa. Their use appears to have good prospects for the broadband acoustic spectroscopy of rock formations. A standard setup "GEOSCAN-02M" was assembled for studying the process of pulse laser generation of ultrasound [14].

Q-switched YAG:Nd laser was used as a source of light pulses. The characteristic laser pulse width was 10 ns. The pulse repetition frequency could vary in the range of 12–50 Hz. The light pulse energy was measured with a calorimetric-type instrument. The maximum energy in a pulse was 100mJ and could be reduced to the value of 10mJ using light filters. The optical beam radius was 5 mm. The shape of the light pulses was recorded by the photoelectric receiver with resolution of 0.5 ns and by the broadband oscilloscope Textronic TDS 220 (analogue frequency 100 MHz, sampling frequency 1 GHz). The oscilloscope was connected to the personal computer. The resolution time for the optical part of the recording system did not exceed 1 ns.

The elastic wave pulses were excited by absorption of a laser pulse in the optoacoustic transducer made of polymer. The transducer and the specimen were put into the measuring cell with immersion liquid. The pulse passing through the specimen was recorded by the broadband piezoreceiver based on lithium niobate that contacts the immersion liquid. The piezoreceiver through the pre-amplifier was connected to

oscilloscope Textronic TDS 220 where the time shape of the signal was monitored. The bandwidth of the electroacoustic path was 100 kHz–30MHz. Subsequent digital processing of the recorded signal profiles permitted finding the frequency dependences for amplitude and phase spectra of recorded signals of elastic waves. The amplitude spectrum was used to restore the attenuation coefficient, and the phase spectrum was used to restore the frequency dependence of the phase velocity of longitudinal waves.

## II. RESULTS

Fig. 1 shows the reference pulse passing through the measuring cell with distilled water. In this pulse the compression and rarefaction phases are observed with amplitude relation 5:1. The duration of the compression phase is less than 100 ns. The rarefaction phase appeared due to diffraction of the unipolar reference signal when propagating in the immersion liquid. The amplitude spectrum of the reference signal is 0.3–10 MHz at level 0.5.

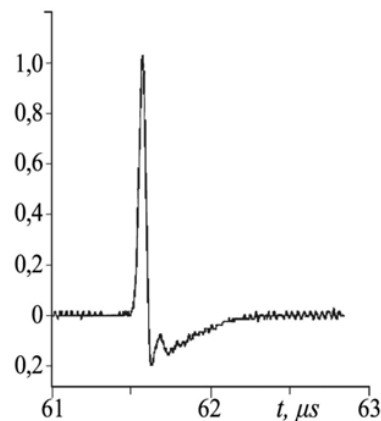


Fig. 1 The reference pulse

This work studied the cubic-shaped specimens of the Karelian gabbro with the rib length 3 cm. In specimens were produced horizontal cracks by the ultimate strength of the uniaxial compression about  $(300 \pm 10)$  MPa. The coal samples of the Kuznetsk Basin were the round plates with thickness of 3–5 mm and diameter of 4 cm.

The preliminary crack localization in gabbro samples was done by laser ultrasonic echoscopy [14]. Scanning was performed on the sample surface and the image of the section plane with the crack was plotted using the computer processing of signals. As the ultrasonic pulse passed through the area without cracks, diffraction and dissipation in the inhomogeneities of the sample resulted in the reduction of the compression phase amplitude by 15 times and in a significant increase of the rarefaction phase amplitude as compared to the compression phase (in Fig. 2, curve 1; the amplitudes of the phases become equal).

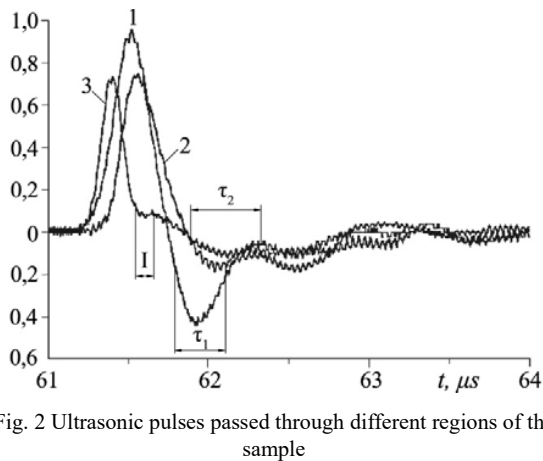


Fig. 2 Ultrasonic pulses passed through different regions of the sample

The pulse duration increases by 2 times due to dissipation of the high-frequency part of the spectrum where frequencies of not greater than 3 MHz remain. Since the crack location was known, the second area of scanning passed through the crack beginning. In this case there was a nonlinear transformation of the signal shape observed (Fig. 2, curve 2), it revealed in the sudden reduction of the rarefaction phase amplitude by 3 times whereas its duration increased by 2 times as compared to the value for the signal passing through the area with no cracks. The compression phase amplitude only reduced by 1.2 times, and its duration changed little.

As the reference signal passed directly through the middle of the crack, the time-separation of two phases of the bipolar pulse (Fig. 2, curve 3) was observed on the background of a sudden reduction of rarefaction phase amplitude. The compression phase velocity was  $(6100 \pm 200)$  m/s, and the rarefaction phase velocity was  $(5700 \pm 200)$  m/s.

When the properties of the coals were studied, the immersion method could not be used because of their high porosity. To excite the ultrasonic signals, light filter C3C-22 was used as an optoacoustic generator; its absorption of the laser pulse resulted in a series of ultrasonic signals of longitudinal waves, the first of which corresponded to the single pass through the light filter and the subsequent ones were re-reflected from C3C-22 boundaries. The delay time for each subsequent pulse equaled the time of the double pass through the light filter. The acoustic track of the reference signal was studied with the first two bipolar sounding signals which duration was 50 ns (Fig. 3 (a)). Subsequent pulses were intensely absorbed when passing through coal samples. These pulses, through a thin contact layer of the viscous liquid, reached the surface of coal samples covered by a thin layer of protective lacquer to prevent the viscous liquid ingress into pores. The characteristic acoustic tracks of signals passing through the samples of 3.8 mm and 5 mm thickness are shown in Figs. 3 (b) and (c) respectively. It is seen in those figures that the pulse shape changes greatly as the signals pass through the sample. The compression phase duration for level 0.5 becomes 300 ns (increases by 6 times), whereas the rarefaction phase duration – more than 1.0  $\mu$ s. It means that only frequencies below 2.5 MHz pass through the sample

during the compression phase, whereas during the rarefaction phase the frequency range is limited on the higher side by 1 MHz. The nonlinear distortions of the pulse shape are also revealed in the fact that a horizontal section appears between the compression phase and the rarefaction phase in the pulse that passed through the sample (area I Figs. 3 (b), (c)).

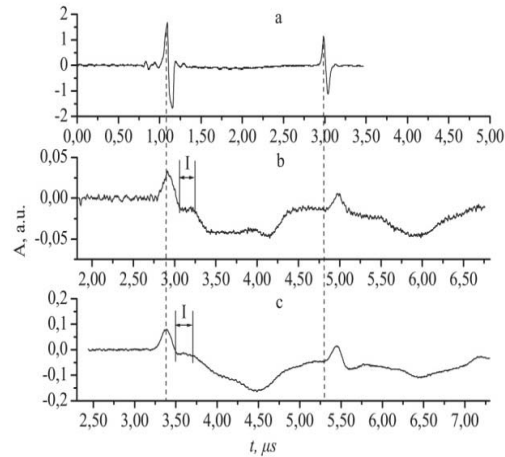


Fig. 3 The acoustic tracks of the reference signals and the pulses passed coal samples

This section shows that the propagation rates are different for the compression phase (2100 m/s) and the rarefaction phase (less than 1600 m/s). Crack opening takes place during the rarefaction phase, which results in the reduction of the ultrasound propagation velocity and absorption of the high-frequency part of the spectrum. The prolonged rarefaction phase means that after passing through the latter, the sample does not revert back to its initial state. When the second pulse passes through such a sample, the velocity decreases (from value 2100 m/s to 1900 m/s for the compression phase). Attenuation of the second pulse appears to be greater than that of the first one. The compression phase amplitude of the first pulse decreases by 25 times when passing through the sample of 3.8 mm thickness, and that of the second one – by 30 times.

### III. CONCLUSION

The research has shown that during propagation of powerful ultrasonic pulses in the geo-medium with cracks, nonlinear transformation of their time profile is observed. This transformation is revealed in a sudden reduction of the rarefaction phase amplitude and increase of its duration. These properties can be used during nondestructive evaluation of fractured media.

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