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Nonlinear acoustic phenomena in a quartzite rod resonator

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HIGHLIGHTS

- The results of experimental and theoretical studies of nonlinear acoustic phenomena in a quartzite rod resonator are presented.
- Analytical description of the observed phenomena is carried out within the frames of the phenomenological state equations containing hysteretic, dissipative and reactive nonlinearity.
- The values of quartzite acoustic nonlinearity parameters are determined.

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ABSTRACT

Here we have presented the results of experimental and theoretical studies of nonlinear acoustic effects (such as low-frequency amplitude-dependent losses, resonant frequency shifts, and high harmonic generation as well as a damping and carrier phase delay of weak ultrasonic pulses under powerful low-frequency pumping wave) in a rod resonator made of a crystalline rock – quartzite. Also, we have given an analytical description of the observed phenomena within the frameworks of the phenomenological equations of state that contain low-frequency hysteretic nonlinearity and both dissipative and reactive high-frequency nonlinearities. Comparison of experimental and analytical amplitude–frequency dependencies of the nonlinear phenomena allowed us to determine quartzite acoustic nonlinearities parameter values.

1. Introduction

The topical questions of modern nonlinear acoustics include the following:

(i) experimental study of nonlinear acoustic phenomena (NAP) in the micro-inhomogeneous [1,2] (or mesoscopic [3–5]) solids possessing a high acoustic nonlinearity,
(ii) determination of the mechanism of an anomalously high nonlinearity of these media,
(iii) establishment of amplitude–frequency dependencies of the NAP,
(iv) deriving of the nonlinear equations of state of these media,
(v) theoretical description of nonlinear wave processes (NWP) in such media and,
(vi) determination of their acoustic nonlinearity parameters.

The topicality of these questions can be explained by the fact that the traditional or "classic" five- (or nine-) constant theory of elasticity [6,7] designed to describe the weakly nonlinear homogeneous solid media does not explain the NWP

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regularities observed in experiments involving highly nonlinear micro-inhomogeneous media, and since a "universal" microscopic theory which would make it possible to adequately describe the NWP in such media does not exist. The high acoustic nonlinearity of the micro-inhomogeneous solids is due to the micro-defects present in their structure (dislocations, cracks, grains, etc.). Such defects are nonlinear, and, as a rule, they have greater compressibility compared to the surrounding homogeneous medium. Thus, it is them that define the high nonlinearity of micro-inhomogeneous solids at sufficiently high defects' concentration [8].

Many polycrystalline rocks (granite, marble, sandstone, limestone, magnesite), metals (copper, zinc, lead), and granular media belong to strongly nonlinear materials. In the low-frequency (LF) range such media show a hysteretic nonlinearity, while in the high frequency (HF) range they show both dissipative (inelastic) and reactive (elastic) nonlinearities [8]. As a rule, amplitude–frequency dependencies of NAE caused by hysteretic, dissipative, and reactive nonlinearities of micro-inhomogeneous media are different. This fact creates a possibility of separating the contributions of each specific type of nonlinearity in the manifestation of various LF and HF nonlinear phenomena.

The most appreciable manifestations of nonlinear properties of media take place at relatively high amplitudes of LF standing waves. These manifestations are easily realized in resonators with a high Q-factor at their resonant frequency [1,2,4,5,8–12]. Hysteretic phenomena of amplitude-dependent internal friction (ADIF) (such as nonlinear losses, resonant frequency shift, and higher harmonic generation, as well as the phenomena caused by dissipative and reactive nonlinearity as the damping of weak ultrasonic pulses and their carrier phase delay in the field of LF powerful pumping) were observed in the rod resonators made of polycrystalline solids.

In various media, the same nonlinear effects often manifest themselves in different ways. Therefore, the establishment of the amplitude–frequency dependencies of the NAP in micro-inhomogeneous media is one of the main problems in the experimental studies of the NWP. The fundamental purpose of these studies is to identify the mechanism and to define the parameters of the acoustic (hysteretic, dissipative, and reactive) nonlinearity of the micro-inhomogeneous media. On the practical side, these studies play a key role in the development of nonlinear acoustic methods for diagnostics of micro-inhomogeneous media and materials. In order to solve such problems, it is necessary to know the nonlinear equations of state of these media and to obtain the accurate analytical solutions of the corresponding nonlinear wave equations which in their turn need be compared with the results of experimental studies of the NAP. The phenomenological equations of state are often successfully applied to describe the nonlinear acoustic (elastic and inelastic) properties of the micro-inhomogeneous media. Such equations are basically postulated on the basis of the analysis of results of experimental investigations of the NAP. Therefore, they, as a rule, can adequately describe these results.

Here we have presented the results of experimental and theoretical studies of NAP arising from (i) self-action of longitudinal LF wave, and (ii) interaction of longitudinal LF and HF harmonic acoustic waves in the rod resonator made of polycrystalline rock –quartzite. Also, we have given an analytical description of the observed NAP within the frameworks of the phenomenological equations of state that contain the low-frequency hysteretic nonlinearity and both high-frequency dissipative and reactive nonlinearities.

2. The ADIF and hysteretic equations of state of the polycrystalline solids

In order to describe the nonlinear wave processes in micro-inhomogeneous solids the equations of state containing hysteresis nonlinearity are increasingly applied in acoustics [2,4,5,8,12–36]. The idea of defects of the crystal lattice as a cause of the mechanical hysteresis of solids was proposed by Prandtl as far back as 1913 [37] and in 1940 Read proved experimentally that plastic strain effects amplitude-dependent internal friction of metals and suggested that this phenomenon is the result of the movement of dislocations [38].

Now we shall make a short digression. The direction, in which hysteretic properties of solids are connected with hypothetical hysteresis elements of the media – hysterons, has been intensively developed recently in nonlinear acoustics [22–24,28,29,32–34]. The nature of such hysterons is not associated with any defects of media. In these studies it is supposed that media consists of hysterons with a certain distribution in their parameters. Further, on the basis of this assumption, the media microscopic equation of state is derived. It goes without saying that it turns out hysteretic. Earlier, magnetic hysterons have been previously proposed to explain the magnetic hysteresis of magnetic materials [39–41]. However, the physics of magnetic and mechanical hysteresis (for magnetic and elastic materials) is different. Therefore, the analogy regarding the transferring of the hysteretic magnetic properties of magnetic materials on hysteretic mechanical (acoustic) properties of elastic nonmagnetic materials by attracting the hypothetical mechanical hysterons is viewed at least doubtful in its basis. Besides, the behavior of mechanical hysteron is also represented as strange and unreal because of the fact that the hysteron strain tends to infinity at an indefinitely small excess of a stress of a certain final value, while majority of solids (with the exception of rubber-like materials) collapse at quite small and finitely strains exceeding $10^{-4} - 10^{-3}$. Thus, the hysteretic equation of state, being received on the basis of the hypothetical hysterons, will be actually inapplicable to an adequate description of the deformation of real micro-inhomogeneous media. In order to analytically describe the results of experimental studies of NWP in a certain material it is necessary to know its phenomenological equation of state which in its turn can be obtained on the basis of the analysis of NWP regularities in this material. Afterwards, knowing the phenomenological equation of state of a specific material, it is possible to create both a model of the medium and its microscopic equation identical in its form to the phenomenological one.

Hysteretic properties are common to many micro-inhomogeneous solids, especially to "soft" metals and rocks. However, it would be wrong to believe that there is a universal hysteretic equation of state for all such media with certain numerical