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Phase conjugation of ultrasound waves in comparison with backscattering in disordered medium

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HIGHLIGHTS

- The theory of ultrasound wave phase conjugation in disordered scattering media is developed.
- The data of comparative theoretical and experimental study of ultrasound wave phase conjugation and coherent backscattering phenomena are presented.
- The qualitative difference of the statistical properties of phase conjugate and backscattered waves is demonstrated.
- Experimentally observed correlation of the mean values of phase conjugate wave amplitude and backscattered wave intensity is in quantitative agreement with the developed theory.
- The advantages of wave phase conjugation technique for testing of randomly scattering media are discussed.

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ABSTRACT

Ultrasound wave phase conjugation in randomly scattering media is studied experimentally and treated theoretically in comparison with ordinary backscattering phenomenon. The experiments are carried out on a scattering sample made of a cylindrical agar gel matrix containing a set of glass micro-spheres of 300 μm diameter. The sample was immersed in water and turned slowly for simulation of a statistical ensemble of scatterers. Phase conjugation of the scattered acoustic waves at frequency 10 MHz was implemented by the parametric technique. The signals of backscattered (BSW) and phase conjugate (PCW) waves were detected by the same ultrasonic transceiver. In contrast with the stochastic behaviour of the BSW signal, the PCW amplitude is found almost regular and insensitive to the statistical features of the scattering ensemble. The mean values of amplitudes and the signal to noise ratios for PCW are one order of value higher than for BSW. A variation of the number of scatterers in the aperture of the incident acoustic beam revealed the proportionality of the mean values of PCW amplitude and BSW signal intensity. The results are in quantitative agreement with the developed theory. The advantages of the phase conjugation technique in comparison with the backscattering method for testing of randomly scattering media are discussed.

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1. Introduction

Coherent multiple scattering in disordered media still belongs to the hot topics in various branches of the fundamental wave physics: acoustics, optics, electrodynamics [1–6]. Time reversal transformation of acoustic and electromagnetic waves under multiple scattering was proposed as a mean for achievement of super-resolution over the diffraction limit [7–9]. Coherent backscattering of acoustic waves was studied experimentally and described theoretically [10,11]. Application of coherent scattering of phase conjugate ultrasound waves (PCW) for testing of bubbly liquids was recently demonstrated [12]. As usual in experiments on wave phase conjugation the measured value is the signal received by the transceiver used for emission of the incident testing waves. The amplitude of the received signal contains information on the density of the scatterers and on their scattering amplitudes, while the phase of the signal detects the movement of the medium [13].

The difference between coherent backscattering and phase conjugation can be explained on an example of an imaginary experiment with two plane transceivers electrically connected in series and excited jointly by an electrical tension. If the angle α between the axes of the transceivers is nonzero the intensity of the total electrical signal generated by backscattered waves will be equal to the sum $2I$ of the intensities I received individually by each one transceiver. Only if the transceivers are parallel ($\alpha = 0$) the received signals are superposed in phase and the total intensity increases twice up to $4I$. In contrast, the signal generated by the phase conjugate waves is always superposed in phase on transceivers independently on α and the total intensity is always twice the sum of the individual intensities. The enhancement of intensity for time reversal focusing was described in [14]. More over, as it is shown below, the statistical features and energetic efficiencies of backscattering and phase conjugation processes are significantly different even in the typical experimental conditions with a single plane transceiver.

The aim of the present paper is a comparative study of ultrasound wave phase conjugation and backscattering phenomena in a disordered medium. Coherency of PCW back propagation in randomly scattering media requires a special theoretical analysis for interpretation of the experimental data. In the theoretical part of the present paper we reduce the problem of PCW multiple scattering to the classical problem of energy flux of scattered waves. For experimental comparison of PCW and BSW properties we use as a scattering medium a set of glass micro-spheres embedded into a cylindrical agar gel matrix immersed in water. The statistic ensemble of the scatterers is simulated by a slow rotation of the scattering medium in the acoustic field. Wave phase conjugation is implemented by the supercritical parametric technique based on electromagnetic modulation of sound velocity in magneto-acoustically active solid [15–18]. Correlation between the PCW amplitude and the mean value of BSW signal intensity is studied under the regular variation of position of the scattering object relatively to the aperture of the incident ultrasound beam. The experimental results are compared with the theoretical predictions.

2. Theoretical model

We consider propagation of harmonic wave $\psi(\vec{r})e^{i\omega t}$ of acoustic pressure in a scattering medium in the framework of the classic formalism (see [19]):

$$\left[\hat{L}_0 - \hat{V}(\vec{r})\right] \cdot \Psi = 0, \tag{1}$$

where the $\hat{L}_0 = \Delta + k_0^2$ is the Helmholtz operator of homogeneous medium free of scatterers, $\kappa_0 = \omega/c_0$ is the correspondent wave number, $\hat{V}(\vec{r})$ is the operator of perturbations caused by the presence of scattering inclusions [20]:

$$\hat{V}(\vec{r}) = \frac{\partial}{\partial x_i}\left(\frac{\rho - \rho_0}{\rho}\frac{\partial}{\partial x_i}\right) - k_0^2\left(\frac{\rho_0 c_0^2}{\rho c^2} - 1\right). \tag{2}$$

Here ρ and c are the density and sound velocity in the substance of inclusions randomly distributed in a surrounding medium with parameters ρ_0 and c_0.

The problem (1) is equivalent to the integral equation

$$\psi(\vec{r}) = \psi_0(\vec{r}) + \int d\vec{r}' G_0(\vec{r} - \vec{r}')\hat{V}(\vec{r}')\psi(\vec{r}') \tag{3}$$

where $\psi_0(\vec{r})$ is the incident wave field, $G_0(\vec{r} - \vec{r}') = e^{-ik_0|\vec{r}-\vec{r}'|}/4\pi\left|\vec{r} - \vec{r}'\right|$ is the Green function for a medium free of scatterers. The scattered field is described by the integral in Eq. (3). We suppose for determinacy that the incident field is generated by a transceiver with homogeneous distribution of the normal displacement velocity v_n over the surface S. So the incident wave function is expressed as the Rayleigh integral:

$$\Psi_0(\vec{r}) = 2i\omega\rho_0 v_n \int_S d\vec{r}_S \cdot G_0(\vec{r} - \vec{r}_S). \tag{4}$$

We assume also that the phase conjugate wave $\psi_{PCW}(\vec{r})$ is emitted from the surface Σ of the phase conjugator:

$$\psi_{PCW}(\vec{r}) = \int d\Sigma \frac{\rho_0}{\rho}\left(\frac{\partial}{\partial n_\Sigma}G(\vec{r}, \vec{r}_\Sigma) - G(\vec{r}, \vec{r}_\Sigma)\frac{\partial}{\partial n_\Sigma}\right) \cdot \psi^*(\vec{r}_\Sigma) \tag{5}$$

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