4. Conclusion

The considered examples of the acoustic diagnostics of nonlinear waves demonstrate new physical phenomena in granular rocks and the ocean. The metastable state of the granular media is an important condition for studies of acoustic effects on percolation in rocks. The nonlinear interaction of internal waves determines the transformation of the tidal energy into oceanic turbulence. The acoustic diagnostics prove to be effective for studying the dynamics of processes at the continental shelf.

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Parametrically phase-conjugate waves: applications in nonlinear acoustic imaging and diagnostics

V L Preobrazhenskii

1. Introduction

Wave phase conjugation (WPC) is typically understood as a wave process whose time development is the reverse of an arbitrarily specified incident wave. The interest in acoustic WPC stems from the ability of phase-conjugate waves (PCWs) to automatically focus onto objects that scatter the incident wave and to compensate the phase distortions of wave propagation in heterogeneous refractive media. Various applications of these properties for ultrasonic diagnostics, therapy, surgery, nondestructive evaluation, and underwater communications have recently been intensely discussed.

Comprehensive research of physical principles and mechanisms underlying the ultrasonic WPC began more than 20 years ago and was stimulated considerably by the results in the nonlinear optics for WPC of light. Since the early 1980s, the mainstream objective of several years of research has been to find adequate approaches to the problem of generation of ultrasonic PCWs in various condensed media. The systematized results of this research are reviewed in [1, 2].

The most promising techniques of acoustic PCWs, including phase conjugation of ultrasonic waves in parametrically active solid media such as piezoelectrics and magnetics [3 – 6] and time reversal of the acoustic signals in receiving and transmitting multichannel electronics [7, 8], appeared in the late 1980s – early 1990s. WPC techniques based on time reversal in waveguides and cavities with multiple reflection are being intensely developed [9, 10]. The supercritical parametric phase conjugation of magnetoelastic waves in magnetostrictive ceramics [2, 4, 11] is an effective way to produce PCWs with frequencies from several megahertz to several dozen megahertz for applications in medicine and defectoscopy. The fairly strong coupling between elastic and magnetic subsystems of spinel ferrite-based ceramics allows an effective modulation of the speed of sound by a high-frequency magnetic field. The modulation depth may then considerably exceed the threshold of parametric instability for the longwave phonons at room temperature. Under the conditions of supercritical pumping, a parametrically active element works as a source of stimulated phase-conjugate phonon pairs providing the giant (over 80 dB) amplification of the PCW compared with the incident wave. The ceramic technology allows manufacturing active elements of a wide variety of shapes and sizes according to the requirements of specific applications.

A numerically modeled animation of supercritical amplification in an active medium taken from [12] is available in Supplement 1 to the on-line version of this report.

The possible uses of magnetoacoustic PCW methods to autofocus ultrasound in liquid and solid matter and to autotarget ultrasonic beams to sound-scattering objects in liquids have been demonstrated in a set of experiments (reviewed in [2]). A stroboscopic visualization of autotargeting of

ultrasound to air bubbles rising in water [13] is given in Supplement 2 to the on-line version of this report. The use of parametric WPC to compensate the phase aberrations in linear ultrasonic imaging is shown in [14, 15].

The combination of phase conjugation with giant conjugate-to-incident wave amplification is especially interesting for research and applications of WPC in nonlinear acoustics. Whereas the experimental and applied research on linear acoustic PCWs have been actively developing since the late 1980s (see [2, 16]), the nonlinear acoustics of PCWs became a promising field of acoustics a relatively short time ago. The nonlinear acoustics was pioneered in works [17, 18], where nonlinear distortions of wave profiles of parametrically PCWs and retrofocusing of reversed waves in homogeneous nonlinear media were studied experimentally and theoretically. Some results of research on the properties of nonlinear ultrasonic PCW beams and some potential uses of these properties for acoustic imaging are reviewed in [19].

As in optics, WPC in acoustics is a manifestation of the wave-field invariance under time reversal. Under strongly nonlinear conditions, the reversibility of wave processes is usually not ensured, resulting in the specific features of WPC in nonlinear acoustics. In this report, we discuss the physical mechanisms of retrofocusing of ultrasonic PCW beams in nonlinear and heterogeneous acoustic media. The results of the research on retrofocusing under the conditions of giant parametric amplification of PCWs and the phase conjugation of selected harmonics of the incident nonlinear wave are presented [20–23]. The applications of the effects of nonlinear retrofocusing are exemplified by compensation of the phase aberrations in nonlinear acoustic imaging [24, 25]. The potential applications of WPC-based autoconfocal systems for ultrasonic diagnostics of nonlinear inclusions are discussed. We consider the physical principles of the ultrasonic velocimetry based on the interaction of PCWs in the presence of moving scatterers [27]. We give examples of ultrasonic WPC used for the diagnostics of flows in liquid [27, 28].

2. Nonlinearly propagating ultrasonic PCW beams and time reversal

As noted above, the specificity of the WPC problem in nonlinear acoustics is that the propagation of the incident and the phase-conjugate waves is no longer a reversible process. The medium nonlinearity does not by itself violate the field invariance under time reversal, but may result in a considerable acceleration of irreversible dissipative processes. An example of this situation typical for acoustics is the shock distortions of the wave profile formed during the cascade generation of harmonics in a nonlinear medium [18, 29]. The amplification during the generation of the PCW emitted into a nonlinear medium is obviously dependent on the violation of the reversability of the wave process. Finally, the bandwidth of real acoustic WPC systems is usually considerably limited, resulting in a trimmed reproduction of the spectrum of nonlinear waves. Nevertheless, the first experimental and theoretical research data on nonlinear acoustic PCWs [18, 24, 25] have shown that in dispersion-free nonlinear acoustic systems, contrary to nonlinear optics, a partial violation of the field invariance under time reversal does not hinder observation and the use of the effects such as PCW autofocusing and the compensation of phase aberrations caused by inhomogeneous refraction.

3. Retrofocusing of nonlinear PCW beams in a heterogeneous medium

Typical results of the observed retrofocusing of a nonlinear PCW after passage through an aberrating layer are given in Fig. 1 [20]. Figure 1a shows the focal distribution of the sound amplitude broken by the aberrating layer. Figure 1b demonstrates how the focal acoustic field distribution is restored by the parametric PCW. The focal amplitude distribution of selected harmonics of the nonlinear PCW after passage through the aberrating layer is shown in Fig. 3c. As shown in [24, 30], the presented experimental results are due to the spatial and temporal synchronization of the harmonic's phases during their cascade generation in a dispersion-free medium. The harmonic phase synchronization concept was further developed when the selective phase conjugation of separate harmonics of nonlinear waves was studied [22, 23, 25]. These theoretical and experimental studies showed that nonlinear wave spectrum trimming by the narrow-band phase

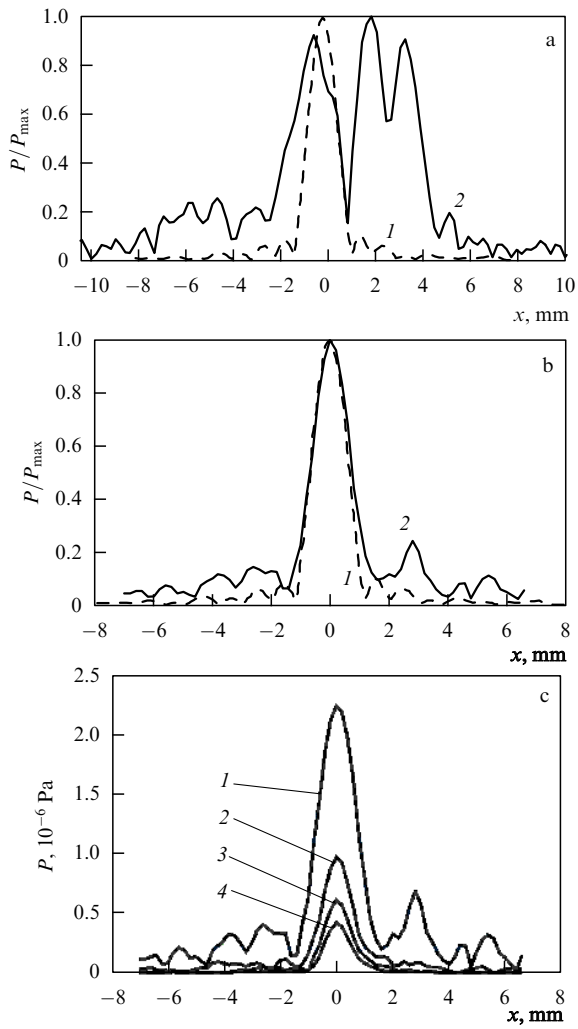

Figure 1. The focal distributions of pressures for the incident and conjugate waves (x is the distance from the axis): (a) for the incident wave without (curve *1*) and with (curve *2*) the aberrating layer; (b) normalized average pressure; curve *1* — for the incident wave without the aberrating layer and curve *2* — for the conjugate wave with the aberrating layer; (c) the amplitudes of the first four harmonics of the conjugate wave with the aberrating layer (the fundamental frequency is 10 MHz) [20].

conjugation of the second harmonic of the incident wave does not hinder the retrofocusing of finite-amplitude PCWs in a heterogeneous nonlinear medium.

4. Principles of nonlinear WPC-based acoustic imaging and diagnostics

The studies of nonlinear WPC phenomena are stimulated by a current trend to use nonlinear acoustic techniques not only for natural applications of high-intensity ultrasound such as lithotripsy, hyperthermia, and ultrasonic technology but also in traditional fields of linear acoustics such as ultrasonic diagnostics and nondestructive evaluation. 'Harmonic imaging' is a rapidly developing field of modern acoustic imaging. It is based on the analysis of harmonics generated by waves of finite amplitudes in the acoustic media in question. The techniques of harmonic imaging can be divided into two main groups. In the first group, the nonlinearity of the medium analyzed is used to form the incident acoustic beam. It should be noted that almost 30 years ago, the second harmonic was proposed to be used for the higher resolution of the acoustic microscope [31]. The number of applications of harmonic imaging for ultrasonic diagnostics is currently growing [32 – 34]. When focussed ultrasonic beams propagate in a nonlinear medium, the focal distribution of the second and higher harmonics of the nonlinear wave is narrower than that of the fundamental harmonics and its side lobes are lower. Besides, the generation of harmonics during wave passage through a thick medium reduces the noise originating from the refractions of the incident wave at the boundaries of the area in question. Taken together, all of the above allows considerably increasing the resolution of ultrasonic diagnostic equipment.

In the second group of harmonic imaging methods, the nonlinear response to acoustic treatment is used to obtain information about the nonlinear parameters of the medium in question and the variations of these parameters due to general or local structural changes (see [35 – 39]). Microcracks in a solid matter lead to the so-called contact nonlinearity, which in turn results in the anomalously amplified nonlinear acoustic response and in the more effective interactions of waves of different frequencies [36, 37]. The special nonlinear properties of solid media are used for the nondestructive evaluation of the materials. The possibilities of diagnostics using changes in nonlinear acoustic properties of biological tissues concurrent with the pathological changes in them are being discussed [40].

The possibility of the giant amplification of PCWs in the supercritical parametric mode permitted the natural expansion of the WPC technique to nonlinear acoustic imaging. The WPC technique has been combined with harmonic imaging in [24, 25]. The use of parametric PCWs for the compensation of the phase aberrations of an acoustic microscope that uses the second harmonic of the conjugate wave to view the object is shown in Fig. 2. The introduction of the aberrating layer to the confocal transmission microscope completely destroyed the image, whereas the use of WPC allowed not only restoring the image produced by the fundamental frequency of the incident beam but also obtaining a higher-resolution image produced by the second harmonic. Given in Fig. 3 are the images obtained by an acoustic microscope in which the second harmonic of the incident beam was selectively phase-conjugated [25]. The

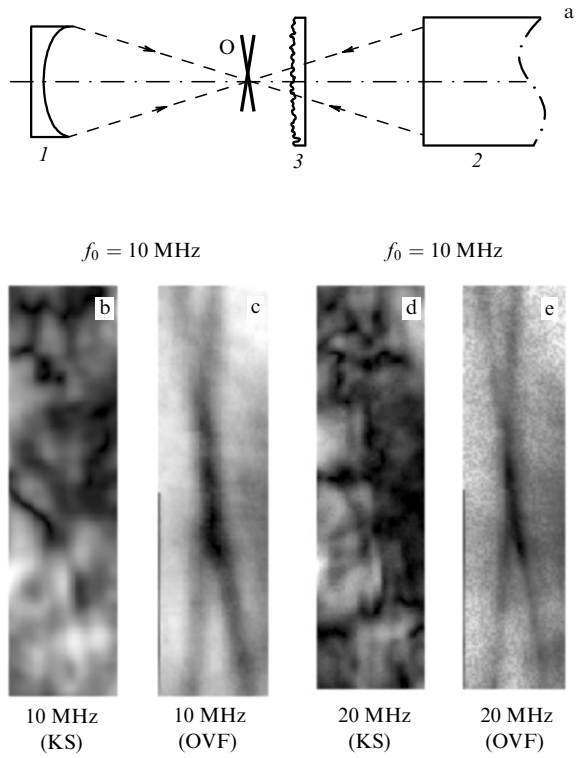

Figure 2. Acoustic images of an object restored by the phase conjugation of the fundamental harmonic of the incident wave: (a) the experimental setup (O is the object, *1* — sound transceiver, *2* — magnetoacoustic PCW amplifier, *3* — aberrating layer; (b, d) confocal microscope (CM) images produced by the fundamental and the second harmonics of the incident wave; (c, e) restored images produced by WPC [25].

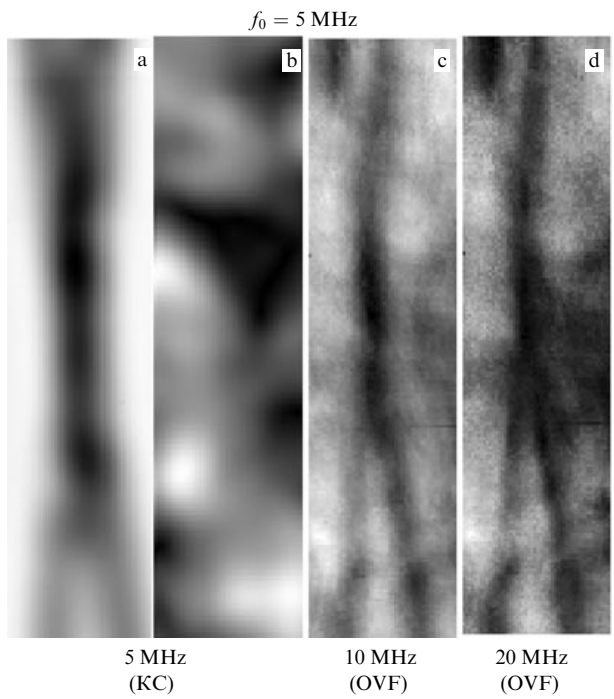

Figure 3. Acoustic confocal images produced by the fundamental harmonic at 5 MHz without (a) and with (b) an aberrating layer. (c, d) Images produced by the phase conjugation of the second harmonic of the incident wave with an aberrating layer at the frequencies 10 MHz and 20 MHz [25].

images are produced with and without an aberrating layer by the fundamental harmonic of the incident wave and by the fundamental and the second harmonics of the conjugate wave. The use of selective phase conjugation of the separate harmonic of the incident wave allows not only compensating the phase aberrations but also considerably increasing the frequency of analysis in the lower order of nonlinearity. The selective phase conjugation of harmonics also permits autofocusing ultrasound onto localized strongly nonlinear objects, which may be used for diagnostic purposes.

The PCW principle can automatically ensure that the acoustic systems are confocal. That, together with the feasibility of compensating for the phase aberrations, is useful for the nonlinear diagnostics of inclusions that are difficult to detect by linear acoustic imaging techniques. A feature of the second harmonic generation in confocal systems, caused by a phase jump of nonlinear sources in the focal plane, allows locally diagnosing the distribution of the nonlinear parameter by the second harmonic of the incident wave [41, 42]. The possibility of obtaining the image of a local inclusion produced by the second harmonic of the focussed PCW is considered in [26]. The geometry of the system and the calculated ration between the amplitude of the second harmonic registered by the sound transceiver and the position of the inclusion in the focal area are given in Fig. 4. Even small inclusions are predicted to generate a second harmonic exceeding the noise as much as the nonlinear parameters of the inclusion exceed those of the acoustic medium surrounding it.

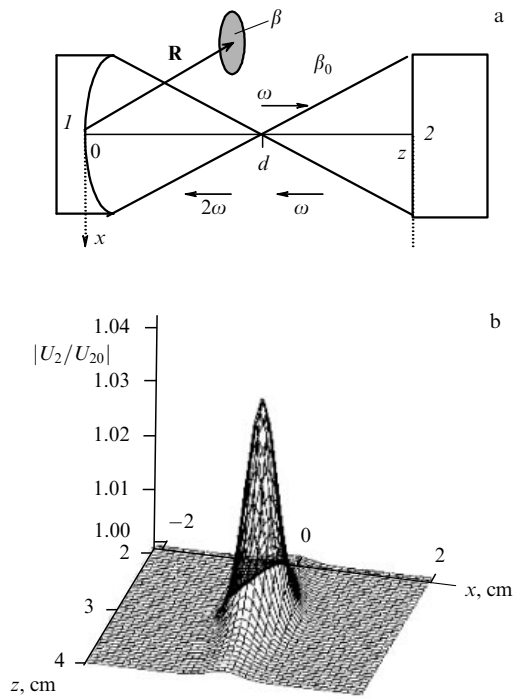

Figure 4. Acoustic imaging of inclusions using the second harmonic of a PCW: (a) the geometry of the experiment (*1* — transceiver, *2* — PCW amplifier, β and β_0 are the nonlinear parameters of the inclusion and the surrounding optical medium, respectively); (b) the response of the second harmonic, given as signal/noise ratio, to a change in position of a spherical inclusion 3 mm in diameter relative to the focus (the experimental parameters are $\omega/2\pi = 10$ MHz, $(\beta - \beta_0)/\beta_0 = 0.1$, $s = 30$ mm, and the transceiver aperture is 15 mm) [26].

5. Applications of WPC for velocity measurements and diagnostics of flows

The possible application of ultrasonic WPC that are targets themselves to a scatterer for measuring the scatterer velocity is demonstrated in [27, 43]. When PCWs of similar frequencies collided near a scatterer in experiments [44, 45], they produced ultrasound of a low difference frequency, with its phase being anomalously sensitive to the displacements of the scatterer. The movement of the scatterer was accompanied by a Doppler frequency shift of the low-frequency wave. Unlike the regular Doppler shift, which is proportional to the carrier frequency, the registered shift was proportional to the doubled frequency of one of the high-frequency waves propagating toward the receiver of the low-frequency sound. The effect is due to phase additions of the conjugate waves when the difference frequency sound wave is produced. A possible application of this effect for measuring the scatterer velocities ranging widely from 0.05 mm s^{-1} to 300 mm s^{-1} at the difference frequency of 1 MHz is demonstrated in [27, 43]. Here, the registered Doppler shift exceeded the regular values of the Doppler shift by an order of magnitude at the given frequency and the velocity of the scatterer.

The PCW principle assumes that the phase of the wave at the source is restored irrespective of the phase shifts in the forward and the reverse directions. The phase is restored in both homogeneous and heterogeneous refractive media. Flows in the medium disturb the wave invariance under time reversal and thus result in a phase shift of the conjugate wave at the transceiver. A phenomenon of this nature observed earlier was the wave front distortions that accumulated during the repeated passage of conjugate waves through a vortex in a fluid [46]. In [27, 28], a beam passing through a flow was scanned, and the PCW phase shifts were analyzed in order to obtain the images of the velocity distribution of the water flows of various geometries. The authors of [28] analyzed not only the phases of the fundamental harmonic of PCWs but also the phases of the second harmonic and of the low difference frequency signals produced by the interaction of the phase-conjugate waves of close frequencies. The experimental setup and the visualized water flow from [28] are given in Fig. 5. In this experiment, a low-frequency wave was generated by the interaction of the 20 MHz second harmonic of the conjugate wave with an additional 19 MHz pulse in the same direction, and the phase of the low-frequency wave was analyzed to produce the image. The use of the second harmonic doubled the registered phase shift, and the acoustic frequency subtraction increased the signal/noise ratio for digital processing of the registered signals by more than an order of magnitude.

6. Conclusion

The results presented here show the effectiveness of the supercritical ultrasonic WPC technique for applications in nonlinear acoustics. In heterogeneous refractive media, the waves are no longer reversible due to the conjugate wave amplification and WPC spectrum trimming. The experimental and theoretical demonstrations of the refocusing of ultrasound in such media are paving the way for the development of new techniques in acoustic imaging and diagnostics. The physical principles of these techniques are to some extent exemplified by harmonic imaging, nonlinear ultrasonic velocity measuring, and the diagnostics of flows. It

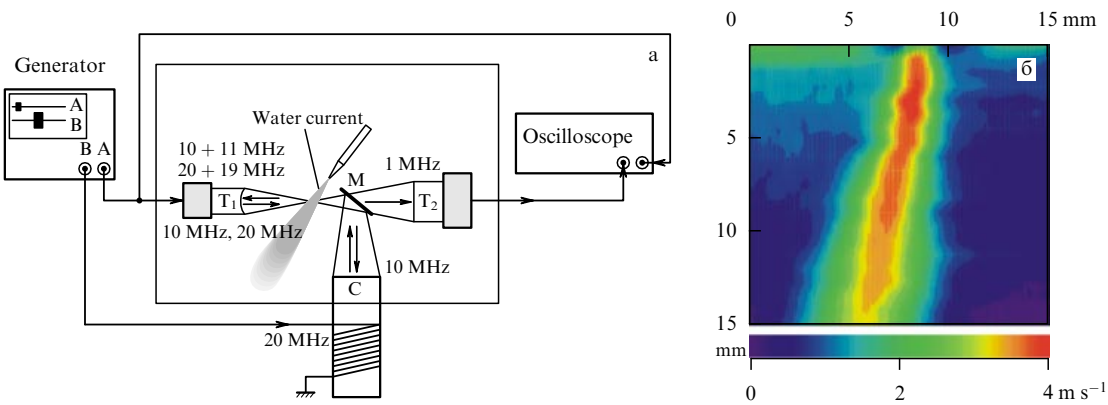

Figure 5. The PCW diagnostics of water flows: (a) the experimental setup (T1 and T2 are the ultrasound source and detector, respectively, C is the PCW amplifier, M is the deflecting plate); (b) an acoustic image of the velocity distribution in a flow [28].

would not be an overestimation to say that nonlinear WPC acoustics has recently become one of the hottest fields in physical acoustics and ultrasonics. The fundamental contribution to this field and to WPC acoustics in general made by the Russian Academy of Sciences is remarkable.

In conclusion, the author thanks F V Bunkin for the initiation and for his constant support in the work on WPC acoustics and the colleagues from the the Joint Russian–French European Laboratory of Nonlinear Magnetoacoustics (LEMAC) for their fruitful collaboration.

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