

The resulting harmonic images are presented in Fig.8. The contrast level of the harmonic image in the agar phantom surrounding the anechoic inclusion progressively disappear. The harmonics due to intrinsic nonlinearity of the phantom are cancelled. Note that a translation of the phantom does not degrade the cancellation ability of the technique.

4. Conclusion

A new way to cancel the harmonics generated during the nonlinear propagation of ultrasound in tissues is proposed. The technique can be adaptive if based on time reversal processing. A simplified approach based on the used of distorted emission waveforms deduced from simulations can also be envisioned. Both techniques require the use of fully programmable transmitter. This paper provides first harmonic cancellation experiments using such a fully programmable transmitter technology. Contrast enhancement is found to reach 15 dB. Further improvements of the technique are in progress. Next harmonic cancellation experiments will be conducted while introducing contrast agents in the medium.

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NONLINEAR ACOUSTICS OF PHASE CONJUGATE ULTRASOUND BEAMS. TEN YEARS OF THE RUSSIAN-FRENCH COLLABORATION

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Overview of nonlinear acoustics of phase conjugate waves (PCW) - the new domain of physical acoustics created by the participants of the Joint Russian-French laboratory LEMAC is presented. The original magneto-acoustic technique of supercritical parametric wave phase conjugation (WPC) is used as a basic method of generation of high intensity PCW. The results of experimental and theoretical studies of nonlinear propagation and interaction of PCW in liquids are considered. Compensation of phase distortions and high quality retro-focusing of PCW in nonlinear and inhomogeneous media in conditions of

break of time reversal invariance (TRI) are observed experimentally and described theoretically. Selective WPC of the harmonics of nonlinear beams and its application for harmonic imaging are demonstrated on an example of the nonlinear acoustic microscopy. Detection of nonlinear inhomogeneities by means of WPC is described. Low frequency wave generation by nonlinear interaction of high frequency PCW and its use for velocimetry of scattering objects in liquid are discussed. Applications of TRI break for ultrasonic WPC- imaging of flows and the advantages of nonlinear modes of flow imaging are demonstrated.

1. Introduction

The studies of nonlinear propagation of phase conjugate acoustic waves (PCW) were stimulated by elaboration of magneto-acoustic technique of supercritical parametric wave phase conjugation (WPC) of ultrasound with giant amplification (see review [1]). Phase conjugation (wave front reversal) phenomena attract attention due to their specific abilities of compensation of phase distortions and automatic retrofocusing on scattering objects in inhomogeneous media. The main properties of PCW are interpreted as a result of time reversal invariance (TRI) of the acoustic fields. Nonlinearity of a medium itself does not break this invariance. Nevertheless a few reasons of violation of TRI appear in nonlinear mode of WPC. Amplification during WPC process makes inequivalence of conditions of propagation for primary and phase conjugate waves. Limitation of frequency band of real phase conjugators embarrasses reproduction of spectrum of nonlinear primary wave. So-called nonlinear attenuation breaks TRI in the vicinity of the shock front. These features make nontrivial the problem of WPC in nonlinear mode. Last ten years this problem became a subject of close Russian- French collaboration of Wave research center of GPI RAS and Institut d'Electronique et de Micro-électronique et de Nanotechnologie (IEMN CNRS, France) (see review [2]). In the present paper we consider the concept of nonlinear acoustics of PCW and demonstrate some basic results in this promising branch of physical acoustics and ultrasonic technology

2. Retrofocusing of nonlinear PCW. Application for harmonic imaging.

The modern methods of acoustic harmonic imaging can be separate on three main groups. One of them uses nonlinearity of acoustic medium surrounding the object under consideration for forming of probing ultrasound beams [3,4]. This approach provides increase of resolution due to relatively low levels of side lobes of harmonics of focused nonlinear beams. Spectral separation and generation of harmonics near the object decreases its masking by parasitic reflections. The second group of methods utilizes the own nonlinear properties of objects for their detection [5]. The third method, known as vibro-acoustography, is quasi nonlinear. It uses acoustic pressure on the object at combination frequency of the incident waves [6]. In this part of the present paper the physical principles of nonlinear imaging by means of WPC are considered for the first group of the methods mentioned above. The manifestations of nonlinear distortions of PCW

profile were observed first in the experiments on diffraction of light on PCW generated by magneto-acoustic conjugator [7]. Numerical simulations and experimental studies of WPC of focused beams have shown high quality

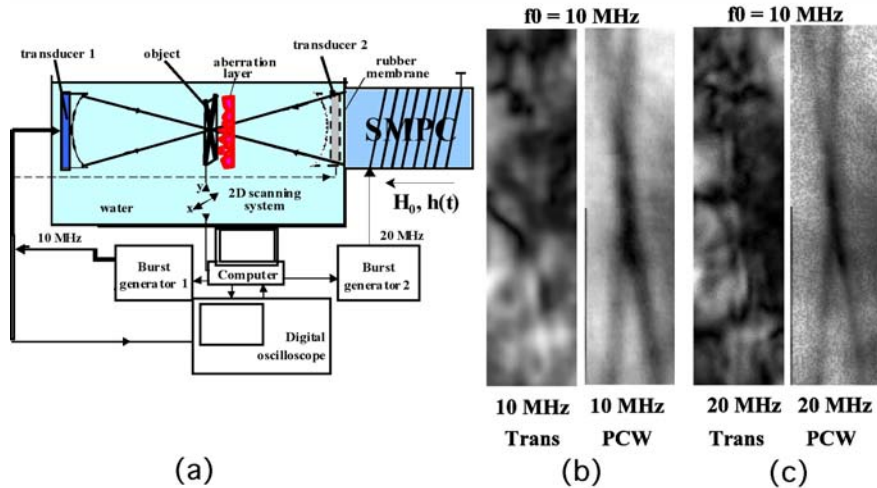


Fig. 1 : Compensation of phase distortions by WPC in harmonic imaging on an example of harmonic microscopy : (a) Experimental scheme of WPC microscope; SMPC is the Supercritical Magnetoacoustic Phase Conjugator; (b) Images obtained with the fundamental harmonics in transmission microscope (left), and using WPC (right); (c) Images obtained with the 2nd harmonics in transmission microscope (left), and using WPC (right);

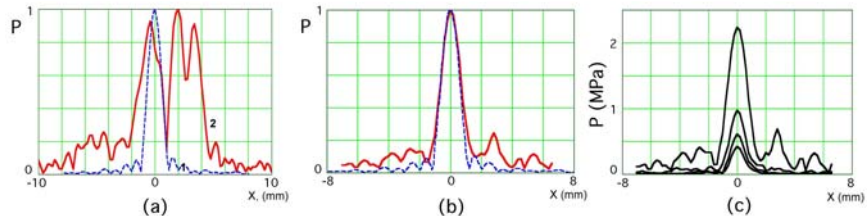


Fig.2 : Focal distributions of the pressure amplitudes: a) incident wave in absence (1) and in presence (2) of the aberration layer; b) dotted line- incident wave, solid line- PCW in presence of the aberration layer; c) four first harmonics of PCW.

retrofocusing of nonlinear PCW in homogeneous medium [8]. The effect took place in spite of TRI break caused by essential difference between intensities of a primary and phase conjugate waves. Retrofocusing of 2nd harmonics of nonlinear PCW in inhomogeneous medium was first observed and studied in ref.[9]. Compensation of phase distortions by WPC in harmonic imaging was shown on an example of harmonic microscopy [9,10]. The typical experimental scheme of WPC-microscope is shown on Fig.1a. An object (two crossed thin wires as an

example) is immersed in water and scans in the focal area of the confocal system formed automatically by the focused transceiver and the phase conjugator. The fundamental harmonics of a primary wave emitted by the transceiver is reversed and amplified by the conjugator. The signals of fundamental and 2nd harmonics of PCW are analyzed for imaging of the object. The improvement of resolution by means of 2nd harmonic analysis, that is the typical advantage of harmonic imaging systems, was clearly manifested in this scheme. More over, it was found that the quality of images was not disturbed neither for fundamental no for 2nd harmonics in presence of an aberration layer between the object and conjugator, while the same layer masked completely the object in transmission mode of the ordinary microscopy (see Fig.1b,c). Observed compensation of phase distortions for 2nd harmonics of PCW is not a trivial result of the principle of time reversal. Narrowband conjugation and amplification of only one fundamental harmonics evidently breaks time reversal invariance. The observed phenomenon was explained theoretically by correlation of phases of all acoustic harmonics generated by cascade in nondispersive inhomogeneous media [9,11]. Retrofocusing of high harmonics generated by PCW passed through an aberration layer was studied experimentally in [12]. The results presented on Fig.2a illustrate destruction of the focal spot of a focused beam passed through an aberration layer. The Fig.2b,c demonstrate compensation of distortions by means of WPC when PCW passed through the same aberration layer towards the focus of the primary wave. The Fig.2c shows the focal distributions of PCW harmonics in this case. The concept of phase correlation of PCW harmonics was developed in studies of narrowband phase conjugation of selected harmonics of nonlinear primary waves [10,13,14]. It was found that WPC of the second harmonics of the focused beam also provides high quality retrofocusing of PCW and compensation of phase distortions in inhomogeneous media. Generation of 2nd harmonics by PCW in this mode was used for analysis of images in acoustic microscopy at frequency of 4th harmonics of the incident wave [10]. Such analysis provides additional increase of resolution of imaging systems at the lowest order of acoustic nonlinearity without decreasing of the signal to noise ratio.

3. Detection of nonlinear objects by means of WPC.

Parametric WPC technique can find various applications for detection of local and distributed nonlinearities in acoustic media. Selective conjugation of harmonics of the incident wave provides automatic targeting of PCW onto nonlinear objects and simplifies their detection in that way. Automatic confocality of imaging systems based on WPC is promising for detection of distributed nonlinear objects invisible by traditional echography. This kind of imaging of nonlinear objects is considered in ref.[15]. Geometry of 3D problem under consideration is shown schematically on Fig.3a. The inclusion of ellipsoidal shape is scanned in the focal area of the system. The nonlinear parameter of inclusion β differs from the one of the surrounding medium β_0 . The

focused transceiver emits the incident wave of frequency ω and receives the backward wave of frequency 2ω . Two modes of 2^{nd} harmonic generation can be used for the detection of an inclusion.

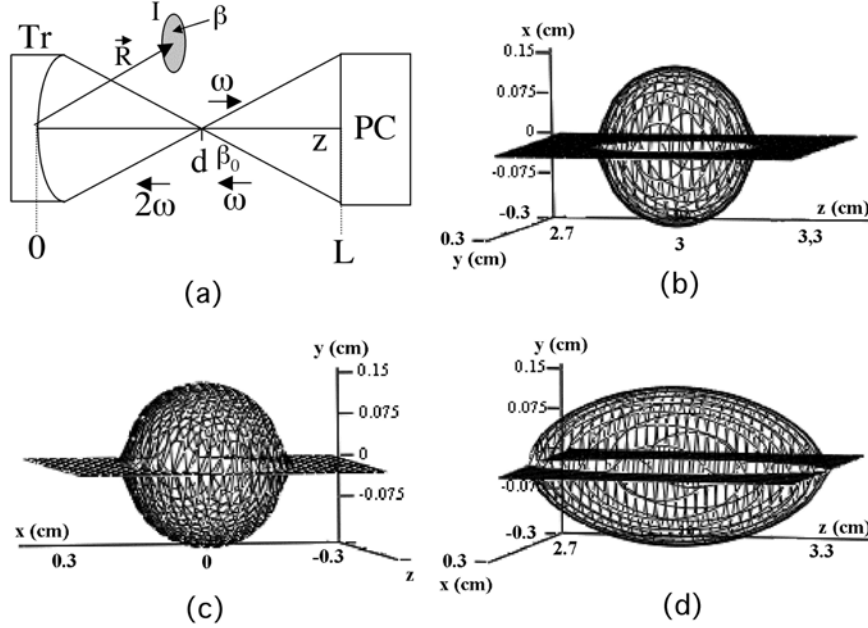


Fig.3 : a) Geometry of the 3D problem of detection of nonlinear inclusion. Tr is a transceiver, PC is a phase conjugator, I is the inclusion with nonlinear parameter β surrounded by the medium with nonlinear parameter β_0 ; b) The shape of inhomogeneity of the nonlinear parameter; c) 2^{nd} harmonic image of the inclusion in C-scan mode; d) image of the same inclusion in B-scan mode.

For the first one the 2^{nd} harmonic wave is generated by the high intensity PCW during its back propagation towards the transceiver. For the second one 2^{nd} harmonics is generated by the incident wave and then is selectively reversed by the conjugator. One can show that the spatial distributions of the 2^{nd} harmonics are different in these two cases but become identical on the surface of transceiver. The received signal $U_2(\mathbf{R})$ depends on the position of the inclusion given by the radius-vector \mathbf{R} . The results of calculation of $U_2(\mathbf{R})$ obtained using KZK equation and Gaussian approximation for distribution of nonlinear parameter of inclusion are presented on Fig.3b,c,d. Numerical calculations carried out for spherical inclusion of diameter 3 mm, fundamental frequency 10 MHz, aperture and focal distance of the transceiver equal to 10 mm and 30 mm respectively show that the maximal excess of the 2^{nd} harmonic signal over background due to inclusion is equal to $|U_2(\mathbf{R})/U_{20}|-1 = 0.4\Delta\beta/\beta_0$, where U_{20} is the signal in the absence of

inclusion and $\Delta\beta/\beta_0$ is a relative perturbation of the nonlinear parameter associated with the inclusion. In spite of small size of the inclusion in comparison with the focal distance its contribution to the 2nd harmonic signal has the same order of value as a perturbation of nonlinear parameter. On Fig.3 the shape of inclusion (Fig.3b) is compared with the image obtained by means of 2nd harmonics of PCW for $\Delta\beta/\beta_0 = 0.1$. The shape of inclusion is represented in the image without visible distortions in C-scan plane (Fig.3c). In B-scan plane (Fig.3d) it is stretched according to the focal length. 3D- model considered in ref.[15] describes only one possibility of WPC application for harmonic imaging of nonlinear inclusions. In particular 4th harmonic analysis using selective WPC of 2nd harmonics in the same experimental geometry increases the contrast of image but slightly deforms it comparing to the shape of object.

4. Principles of nonlinear velocimetry and flow imaging using WPC.

The studies of low frequency emission (LFE) by nonlinear interaction of phase conjugate waves of slightly different frequencies ω_1 and ω_2 in presence of scattering objects in liquid have shown specific features of phase of generated waves [16]. For contra propagating PCW it was found that small variation of the object position can be accompanied by anomalously strong phase shift of generated waves at low combination frequency $\Delta\omega = \omega_1 - \omega_2$. Moving of the object with velocity v leads to Doppler shift of LFE frequency described by the equation [17]: $\Omega_D = \Omega(1 \pm k_s v / k_d c)$, where $k_s = k_1 + k_2$, $k_d = k_1 - k_2$, $k_{1,2}$ are the wave numbers of interacting high frequency PCW. Taking into account inequality $k_s / k_d \gg 1$, such shift is much stronger than the ordinary Doppler effect $\Omega_D = \Omega(1 \pm v/c)$. This feature can find application in Doppler velocimetry of small particles in liquids. WPC technique can also be applied for velocimetry of flows in liquids without scattering objects. WPC transformation presumes by principle restoration of wave phase on the source of emission independently of propagation path of primary and reversed waves. This phenomenon is a direct consequence of time reversal invariance of acoustic field. Mass flows in a propagation medium break TRI and lead to appearance of the phase shift between emitted and received conjugate waves on the transceiver. This feature of WPC can be used for detection and imaging of flows in liquids. The advantage of such approach lies in automatic compensation of all phase incursions accumulated in the process of propagation through immovable part of a medium. The typical experimental scheme of flow detection by means of WPC is shown on Fig.4a [17]. The water flow in a tube immersed in water was used as a model object. The measurements of flow velocity distribution in the cross-section of the tube were made using the focused beams. The tube scanned in direction x perpendicular to the plane of Fig.4a. Doppler phase shift between received and emitted signals as a function of flow velocity v is described in this case by the equation [17]:

$$\Delta\varphi = 2k(r^2 - x^2)^{1/2}(v/c)\text{ctg}\alpha / (1 - v^2 \cos^2 \alpha / c^2),$$

where r is radius of the tube, k is a wave number, α is the angle between the tube and direction of propagation of waves. The results of measurements of flow velocity distribution are shown on Fig.4b by dots [17]. The expected distribution for laminar flow is shown by line for comparison. WPC- imaging of flow distribution in a curved tube is shown on Fig.5. Analysis of phase shift of harmonics of nonlinear PCW provides increase of sensitivity of such imaging method proportionally to the number of harmonics. Experimentally observed phase shifts for fundamental and 2nd harmonics of intensive PCW passed through the tube with water flow are shown on Fig 6a,b by dots. Signal to noise ratio in phase shift measurements was essentially improved using nonlinear LFE effect. When PCW passed through the flow was reflected from the surface of transceiver the additional wave with slightly different frequency and the phase coincident with the initial wave was emitted. As a result of codirectional interaction of reflected PCW with this additional wave the low frequency wave was generated. At that the phase of low frequency wave contained Doppler phase shift corresponding to high frequency of PCW.

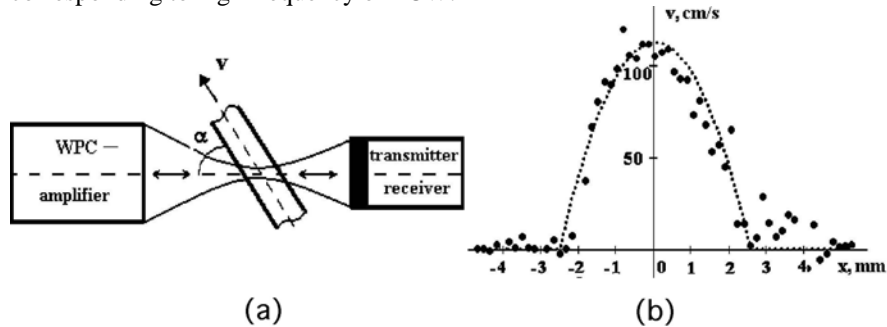


Fig. 4 : a) The scheme of measurements of the velocity of a liquid flow by the Doppler phase shift of the phase-conjugate acoustic wave; b) Velocity distribution of the liquid flow over the cross-section of a tube with a diameter of 5 mm.

The results of measurements of LFE phase as a function of the flow position relatively to the focus of transceiver are shown on Fig.6a by line. The results demonstrate decrease of noise level due to higher precision of digitalization of low frequency acoustic signals. The line on Fig.6b shows the results of combined application of LFE and 2nd harmonic generation for PCW phase shift measurements. In this modification of the method the frequency of additional wave emitted at the moment of PCW reflection was chosen slightly different from 2nd harmonics of PCW. LFE was created in this case by interaction of the additional wave with the 2nd PCW harmonics. The results presented by line on Fig.6b demonstrate correspondent dependence of the LFE phase on position of

flow. Combination of LFE and PCW harmonic generation provided increases of signal to noise ratio and sensitivity of the method.

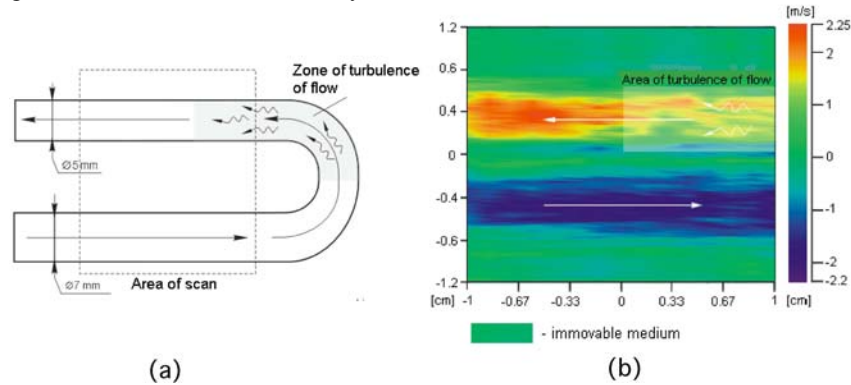


Fig. 5 : Velocity distribution of the liquid flows moving in opposite directions (longitudinal section of the tube):

a) scheme of the experiment, b) flow image obtained using WPC technique.

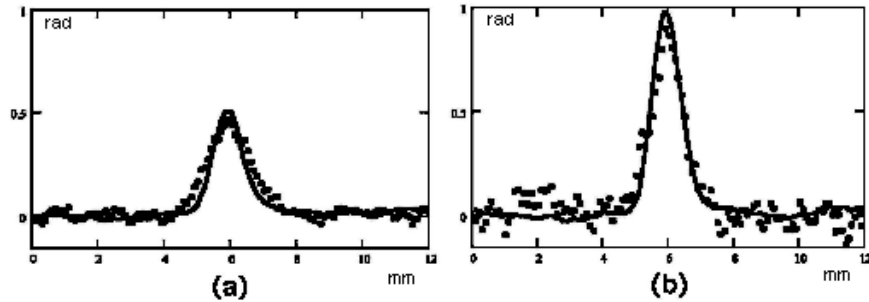


Fig. 6 : Cross- section distribution of Doppler phase shift: a) PCW (10MHz) propagated through fluid jet (dotted curve); LFE (1MHz) generated by ultrasonic wave of 11MHz and PCW (10MHz) propagated through fluid jet (solid curve); b) second harmonics of PCW (20MHz) propagated through fluid jet (dotted curve); LFE (1MHz) generated by ultrasonic wave of 19MHz and second harmonic of PCW (20MHz) propagated through fluid jet (solid curve)

5. Conclusion.

Supercritical parametric WPC of ultrasound is an efficient tool of nonlinear acoustics of phase conjugate waves. The results presented in this paper show that fundamental features of phase conjugate waves of finite amplitude have various applications in nonlinear ultrasonics. Harmonic imaging by means of WPC, nonlinear acoustics of phase conjugate waves in moving media and nonlinear WPC- velocimetry are formed now as new promising directions of Russian-French collaboration in the framework of activity of Joint European laboratory LEMAC.

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ACOUSTIC HOLOGRAPHY AND LASER VIBROMETRY TO
CHARACTERIZE VIBRATION OF PIEZOCERAMIC AND
PIEZOCOMPOSITE TRANSDUCERS USED IN ULTRASOUND
THERAPY

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Acoustic pressure radiated by piezoelectric sources can be predicted based on the normal velocity distribution along vibrating surface. However, up to now, there are no reliable direct methods of surface vibration measurement in liquids. The transducer vibration is frequently considered as being uniform (thickness mode), which may be incorrect due to transducer structure or due to excitation of Lamb waves in it. In this work, a holographic method is developed and experimentally used that enables reconstruction of the radiator vibration pattern. The method includes a measurement of wave amplitude and phase in different points of a plane grid perpendicular to the acoustic axis at some distance from the source, theoretical time reversal of the waveform in each grid-point, and back propagation of the field to the source using the Rayleigh integral. In addition to the holographic approach, vibration of piezoelectric transducers was studied using laser vibrometry. It is demonstrated that the latter method gives wrong results when the transducer is in contact with liquid, because of strong acousto-optic interaction. It is shown that although the acoustic holographic approach has limited spatial resolution (of order of a wavelength), it allows fairly exact prediction of the radiated field pattern.

1. Introduction

Piezoelectric transducers are widely used for ultrasound generation. Structure of the radiated ultrasound field depends on the normal velocity distribution at vibrating surface. The velocity distribution of a real piezoelectric source is usually non-uniform, due to the source structure (e.g. for multi-element transducers) or due to excitation of Lamb waves in a piezoceramic plate in addition to the fundamental thickness vibration mode [1, 2]. Once the surface velocity distribution is known, the acoustic pressure field can be calculated with a good accuracy using Rayleigh integral or angular spectrum approach [3-8]. Therefore, developing of experimental methods for characterizing of ultrasonic transducer vibration is of great importance. In this paper two methods are studied and compared for measuring of the normal velocity distribution at an ultrasonic transducer surface: acoustic holography and laser vibrometry.