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New applications of magneto-acoustic phase conjugation

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Résumé :

Par ses propriétés d'invariance par retournement temporel et d'amplification géante, la conjugaison de phase magnéto-acoustique a déjà montré de nombreuses potentialités d'applications. On montrera que lorsque que l'on brise cette symétrie temporelle, les déphasages induits peuvent être exploités pour d'autres applications comme la vélocimétrie non intrusive.

Abstract :

The results of theoretical and experimental studies of application of parametric wave phase conjugation (WPC) for ultrasonic velocimetry of flows are reported. 3D-simulation of propagation of phase conjugate waves (PCW) in nonlinear and moving media is developed. Break of time reversal invariance of WPC in moving media is considered as a principle of detection and velocimetry of flows. The results of experimental harmonic imaging of flows in water are presented in comparison with theoretical description. Application of WPC technique for diagnostics of blood circulation is demonstrated on an example of pulsating flow in a real blood vessel "in vitro".

Mots clefs : ultrasound, wave phase conjugation, diagnostics of flows

1 Introduction

Due to its specific properties, wave phase conjugation (WPC) is of interest in various problems of ultrasonic diagnostic. For instance WPC provides restoration of phase of the primary wave on the transceiver antenna after back propagation of the phase conjugate wave (PCW) in static media. In a moving medium this time reversibility of wave processes is broken [1,2]. This leads to an uncompensated phase shift between the emitted and received waves on the antenna after phase conjugation, directly correlated to the media movements. WPC can thus be used for ultrasonic velocimetry and diagnostics of flows in fluids [3,4]. The precision and quality of the results can be further improved when nonlinear modes of propagation and interaction of phase conjugate waves are used [5,6]. As another example, owing to its possibilities of selection and amplification of harmonic components, and automatic con-focality, WPC provides an efficient way of imaging of isoechogenic objects hardly detectable by conventional ultrasonic methods [6]. The efficient technique of phase conjugation is based on parametric interaction of sound with electromagnetic pumping in magnetic media [7]. Modulation of sound velocity by alternative magnetic field of double frequency leads to generation of backward wave with inversed phase and giant amplification. In the present paper, the principle of flow diagnostics using such magneto-acoustic WPC is illustrated by nonlinear imaging of immersed jet in water and by detection of flow circulation in real blood-vessel "in vitro".

2 Phase conjugate ultrasound waves in moving nonlinear media

2.1 Theoretical description

The basic equations of hydrodynamics applied for nonlinear media moving with relatively small velocity V compared to the velocity of sound c can be reduced in the framework of quadratic approximation and for paraxial acoustic beams to the KZK-like equation [6,8]:

$$\pm \frac{\partial}{\partial \tau} \left[\frac{\partial P}{\partial z} - \frac{V_z}{c^2} \frac{\partial P}{\partial \tau} \right] + \frac{1}{c} \frac{\partial V_z}{\partial z} \frac{\partial P}{\partial \tau} = \frac{c}{2} \nabla_{\perp}^2 P + \frac{\beta}{2 \rho_0 c^3} \frac{\partial^2 P^2}{\partial \tau^2} + \frac{b}{\rho_0 c^4} \frac{\partial^3 P}{\partial \tau^3} \quad (1)$$

where P is acoustic pressure, β , ρ_0 and b are respectively the nonlinear parameter, the equilibrium density and the viscosity factor of the medium, and $\tau = t \mp z/c_0$, the upper and bottom signs corresponding to the direct and backward waves respectively.

Considering second harmonic generation one can represent acoustic pressure as a superposition of fundamental and second harmonic components:

$$P = A_1^{\pm} \exp(i(\omega\tau + \varphi^{\pm})) + A_2^{\pm} \exp(i(2\omega\tau + \psi^{\pm})) + c.c.$$

One can show using Eq.1 that synchronization of phases of harmonics known for nonlinear propagation in immovable media remains valid in presence of flows and results in relationship $\psi^{\pm} = 2\varphi^{\pm}$. Thus all variations of phase for fundamental harmonics are doubled for the second one. In the framework of nonlinear geometrical acoustics the rays $\vec{r}_{\perp}(z)$ and phases of the conjugate waves can be described by a system of ordinary differential equations, resulting from Eq.1 [6]:

$$\frac{d \vec{r}_{\perp}}{dz} = \pm \frac{1}{k_0} \vec{k}_{\perp}^{\pm}, \quad \frac{d \vec{k}_{\perp}^{\pm}}{dz} = - \frac{k_0}{c} (\vec{\nabla}_{\perp} \cdot \vec{V}_z) \quad (2)$$

$$\frac{d \varphi^{\pm}}{dz} = \pm \frac{k_0}{c} V_z \mp \frac{1}{2k_0} (\vec{k}_{\perp}^{\pm})^2, \quad \vec{k}_{\perp}^{\pm} = -\vec{\nabla}_{\perp} \varphi^{\pm},$$

The system (2) is completed with boundary conditions on the surface $z=0$ of the transceiver and on the aperture $z=L$ of conjugator:

$$\varphi_+ \Big|_{z=0} = G(\omega) r_{\perp}^2 / \varepsilon^2, \quad \varphi^- \Big|_{z=L} = -\varphi^+ \Big|_{z=L}, \quad \vec{k}_{\perp}^- \Big|_{z=L} = -\vec{k}_{\perp}^+ \Big|_{z=L},$$

here $G(\omega)$ and ε are the gain and aperture of focused transceiver respectively. This system was solved numerically for the experimental geometry described below.

2.2 Immersed jet in water

In this experiment the nonlinear technique combining second harmonic generation and Brillouin scattering of ultrasound in water was used for imaging of an immersed jet. The experimental setup is shown schematically on Fig.1. A water jet was immersed in a water tank under the angle 20° relatively to the (x,z) - plane by the nozzle of 2mm diameter. The nozzle scanned in (x,y) - plane. The focused transceiver T1 emitted 10 μ S ultrasonic pulse of frequency 10MHz. After reflection by the thin glass plate M this pulse was reversed and amplified by magneto-acoustic phase conjugator C. During back propagation PCW generated the second acoustic harmonic 20 MHz that was detected by transceiver T1. The phase shifts of the fundamental and second harmonic components of PCW were measured as a function of the nozzle position. According to the

above prediction the phase shift of the second harmonics was twice higher relatively to the phase shift of the fundamental one.

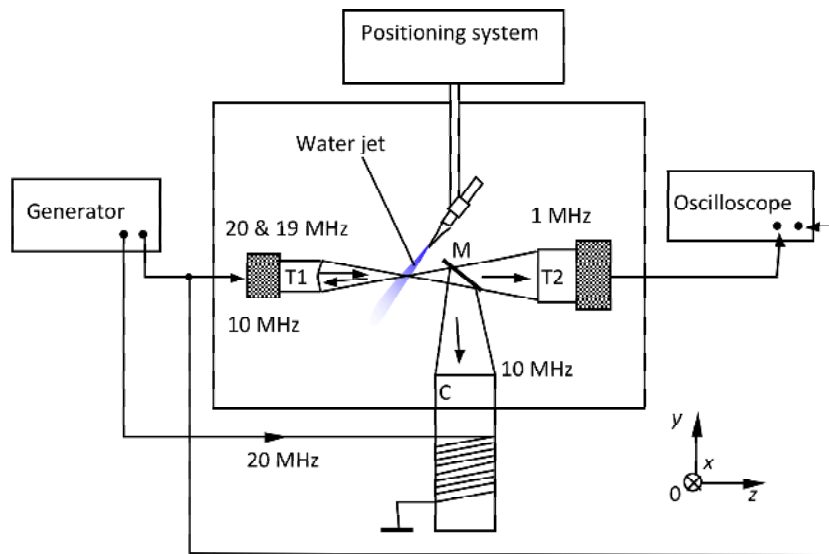


FIG. 1 – The scheme of experimental setup.

The second harmonic pulse reflected by the surface of transducer T1 was mixed with additional wave of frequency 19 MHz. The Stokes component 1MHz of Brillouin scattering, containing the same phase shift as 20 MHz harmonic, passed through the plate M and was detected by transducer T2. The result of measurement of the phase shift of Stokes component as a function of jet position in (x,y)- plane is shown on Fig.2a. For comparison the jet velocity distribution was simulated in laminar approximation by the software COMSOL Multiphysics 3.2. The correspondent phase shift calculated by the approach mentioned in the section 2.1 is presented on Fig.2b. The dependence of the phase shifts on position of the nozzle for the cross sections of the jet near the outlet of the injector is shown on Fig.3. Points on Fig. 3a correspond to the phase shift of the second harmonic 20MHz detected by the transceiver T1. The phase shift of the Stokes component 1MHz detected by the transducer T2 is shown by points on Fig.3b. The results of calculations are presented on Fig.3a,b by lines. The signal to noise ratio for Stokes component is noticeably higher than for second harmonic itself due to smaller error of digitalization of low frequency signal.

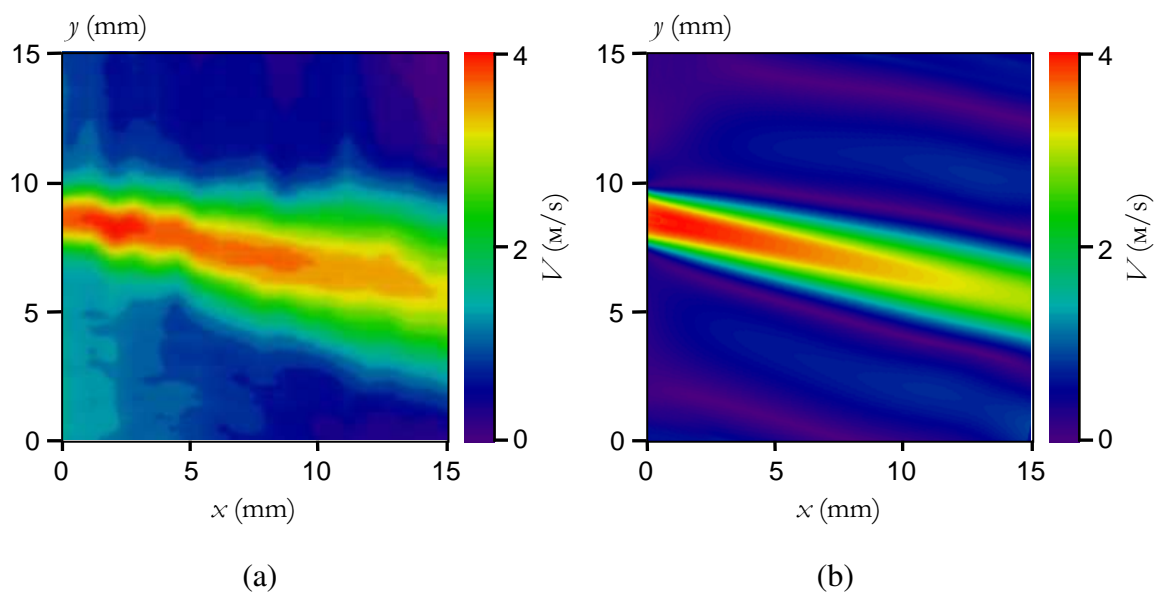


FIG. 2 – The jet image reconstructed from the phase shift of 2nd harmonic of phase conjugate wave: a- experiment, b- numerical simulation.

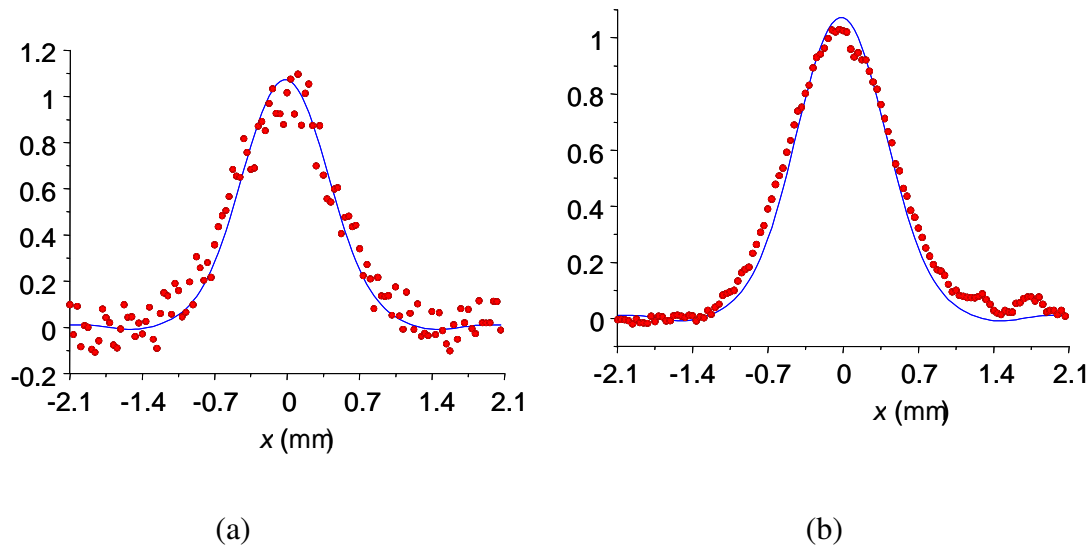


FIG. 3 – The dependence of the phase shifts of 2nd harmonic (a) and Stokes component (b) on position of the nozzle for the cross sections of the jet near the outlet of the injector.

3 Experimental simulation of diagnostics of blood circulation « in vitro »

The principle of wave phase conjugation can be applied for diagnostics of blood circulation. The Fig.4 shows the scheme of experimental setup for detection of pulsating flow in real biological tissue “in vitro”. The pig’s blood-vessel of 4 mm diameter surrounded by adjacent muscular tissue (3) was placed in a water tank in the focal area of the confocal system containing parametric phase conjugator (1) and focused transceiver (4) with operation frequency 10 MHz. Blood pulsations were simulated using the peristaltic water pump (5) with frequency 64 min^{-1} .

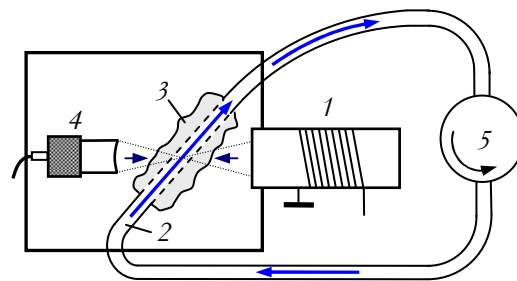


FIG. 4 – The scheme of experimental setup: 1 – parametric phase conjugator; 2 – plastic tubes connected with the peristaltic pump 5, 3 – the blood-vessel with surrounding tissue; 4 – focused transceiver.

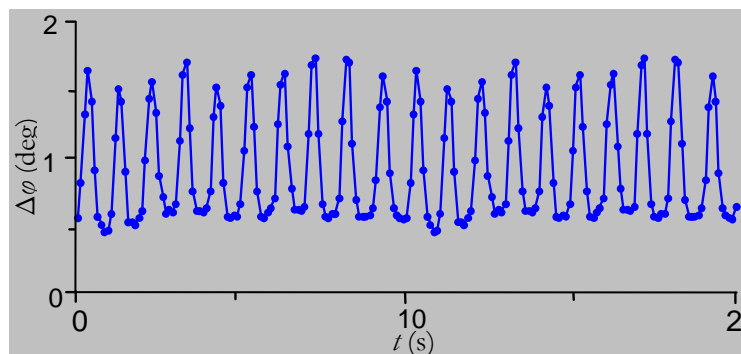


FIG. 5 – Time dependence of the phase shift between incident and phase conjugate waves on the transceiver.

The time dependence of measured phase shift between incident and phase conjugate wave on transceiver is shown on Fig.5. The amplitude of the phase shift reflects variations of flow velocity. The mean value of flow velocity was about 15 cm/s that corresponds to the mean velocity of blood flow in veins.

4 Conclusions

The obtained results show reliability of diagnostics and velocimetry of flows using magneto-acoustic phase conjugation. The results of experimental measurements and imaging are in agreement with the theoretical predictions and numerical simulations. Contrary to the traditional Doppler methods the proposed technique does not need in scattering of ultrasound on moving particles transported by flow and can be used for velocimetry and imaging both of homogeneous and inhomogeneous liquids. The systems based on wave phase conjugation do not require precise positioning and are applicable for electronic scanning by focused beams in the limits of aperture of conjugator without any mechanical displacements. The principle of WPC is useful also for velocimetry of flows in presence of static aberrations.

Acknowledgements

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