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Ultrasonic imaging of static objects through an aberrating layer using harmonic phase conjugation approach

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The main goal of this study is to develop a new image reconstruction approach for the ultrasonic detection of small objects (comparable to or smaller than the ultrasonic wavelength) behind an aberrating layer. Instead of conventional pulse-echo experimental setup we used through transmission, as the backscattered field after going twice through the layer becomes much weaker than the through-transmitted field. The proposed solution is based on the Harmonic Phase Conjugation (HPC) technique. The developed numerical model allows to calculate the amplitude and phase distributions of the through-transmitted acoustic field interacting with the objects and received by a linear transducer array either directly or after passing through an additional aberrating layer. Then, the digitized acoustic field received by the array is processed, phase-conjugated, and finally, numerically propagated back through the medium in order to reconstruct the image of the target objects.

The reconstruction quality of the algorithm was systematically tested on a numerical model, which included a barrier, a medium behind it, and a group of three scatterers, by varying scatterer distances from the source transducer, their mutual arrangement, and the angle of the incident field. Subsequently, a set of laboratory experiments was conducted (at transmit frequency of 2 MHz) to verify the accuracy of the developed simulation. The results demonstrate feasibility of imaging multiple scattering objects through a barrier using the HPC method with better than 1 mm accuracy. The results of these tests are presented, and the feasibility of implementing this approach for various biomedical and NDT imaging applications is discussed.

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1. Introduction

Phase Conjugation (PC) is a general method of reversing the direction of propagation of a wave field while keeping the original spatial distribution of amplitude and absolute phase [1]. A phase conjugating mirror (PCM) is a device implementing this approach. An ideal PCM [2] can produce the time-reversal (TR) effect. Essentially, PC can be treated as a specific case of TR, applicable where it is possible to directly manipulate the phase of the received signals. A general discussion of TR principles is presented by Fink et al. in a set of papers [3–5] and a review letter [6]. As a method, TR has been improved considerably over the last twenty years.

Phase conjugation has been studied both in acoustics [7] and in optics [8–10], where its definition was originally proposed. PCMs described in the literature [2,7,11] may be understood as devices reflecting the incident beam in a phase-reversed sense back along its path [12]. There is a major difference between an ordinary mirror and a phase conjugating mirror [13]. As opposed to ordinary optical mirrors, a phase conjugating mirror corrects the effects of passing through a dispersive medium. In fact, with the phase conjugating mirror the image is not deformed, since the wave field passes through the aberrating element twice. While an ordinary mirror reverses the normal component of the wave vector, a phase-conjugating mirror reverses the whole vector. The reflected beams always retrace their paths back, even through the dispersive medium and regardless of their incidence angle, to focus at the original object. In simple terms, by looking into an ordinary mirror, one could see one's own face, while looking into a phase-conjugating mirror only the pupil of the eye could be seen [14].

Phase conjugation techniques have been proposed in acoustics since the 1980s. A considerable number of studies on this subject have been reported, ranging from basic research to practical ultrasonic applications, including, for example, adaptive ultrasonic

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focusing through distortive (e.g. scattering, inhomogeneous, nonlinear, etc.) propagation media [15].

PC (and TR in general) offer solutions to several problems in underwater acoustics communication, industrial and medical applications. TR is an efficient way to focus the ultrasonic field through an inhomogeneous medium onto a reflective/scattering target, which acts as an acoustic source after being exposed to sound waves. Multiple targets can be detected and identified this way, even with multiple scattering between them Gruber et al. [16].

The ability of phase conjugated or time reversed waves to compensate for phase distortions caused by the propagation medium has proved very useful in ultrasonic focusing applications, especially in the medical field. In therapeutic applications, the adaptive focusing happens in the real medium, but in the imaging applications, the time reversed waves are propagated numerically. As an example, a PC-based procedure is used for the real time tracking and destruction of kidney stones (lithotripsy) with high amplitude pressure fields [5]. Tanter et al. [17] used the same technique to focus pulsed ultrasonic waves through the human skull bone in order to cure brain tumors. White et al. [18] first investigated the defocusing effect of the skull and the resulting degradation of the quality of transcranial ultrasonic brain images. The presence of the skull causes phase shifting of the wavefront and distortion of the pressure field inside the skull, hampering the ability to produce a coherently focused pressure field inside the brain.

In industrial applications, such as nondestructive testing (NDT), the high frequency ultrasound penetrates into metallic and ceramic samples and provides information about the existence of flaws or other defects [13,19]. Using PC or TR techniques helps improve the focusing of the ultrasound field, particularly for samples of complex shape, and facilitate the detection of smaller defects with greater certainty [20].

The concept of PC is very general and can be applied to waves of different types. For example, a PCM was implemented for monitoring the Mediterranean Sea surface and achieved spatial focusing between the source and the receiving array separated by over 6 km [21].

From a mathematical point of view, Harmonic Phase Conjugation (HPC) and Time Reversal are the same concepts. However, there is a major difference between the two from the application standpoint. The time reversal process is adapted for pulsed excitation, while HPC techniques are best compatible with harmonic signals. Therefore the concepts of phase and amplitude distribution measurement of the two types and their usage to produce a back-propagating field are different. In general, for applications where harmonic excitation is possible, it is preferable over pulse excitation, since it delivers higher energy and therefore higher SNR for reconstructed images.

In this study we describe a new ultrasonic HPC-based approach for imaging of small scattering objects through an aberrating layer. At the first step of the algorithm, the acoustic field transmitted through the medium with embedded foreign objects is received by a linear transducer array either directly or after passing through an additional aberrating layer. The information about the original source of the acoustic field is then eliminated from the digitized acoustic field received by the array. In the next step, the remaining (scattered) field component is phase-conjugated and numerically propagated back through the medium. Finally, the field's spatial intensity distribution is represented in the form of an image. The image is expected to show major peaks at the original positions of the scattering objects. After testing the algorithm using a numerical model, a set of laboratory experiments was conducted to verify the accuracy of the developed simulation.

One possible application of this work is the transcranial ultrasonic imaging of small reflective objects dispersed in brain tissue. Such objects could be bone fragments, metal chips, shrapnel, etc. trapped in the brain as a result of a head wound or an injury. The small size of the objects makes them weak reflectors, especially considering the long wavelength of transcranial ultrasound typically chosen to overcome strong attenuation and scattering by the skull. On the other hand, the through-transmitted portion of the acoustic field is much stronger, and therefore the pitch/catch measurement setup is a more attractive option to explore. When choosing between the popular TR and the less explored HPC technique, the latter was selected because it uses higher-power harmonic excitation, necessary to penetrate thick skull bones.

2. Theory and simulation

Fig. 1 shows the general test setup as a base for the developed theory and simulation. An ultrasonic transducer driven by a continuous harmonic signal generates an acoustic wave propagating from right to left in the water. The ultrasound field generated by the source may be altered due to interaction with the scattering objects distributed along the propagation path. The resulting acoustic field is received by a linear array on the left. In the linear approximation, the total field received by each array element can be calculated as a superposition of the source filed (direct path) and the field scattered by the objects. The phase and amplitude information of the total field is recorded by each element of the receiving array to be later used in the image reconstruction process. In this setup, an additional aberrating layer may or may not be present in contact with the receiving array depending on the application, as discussed later in this section.

In general, the intensity of the source field component is much higher than that of the scattered field component. Therefore

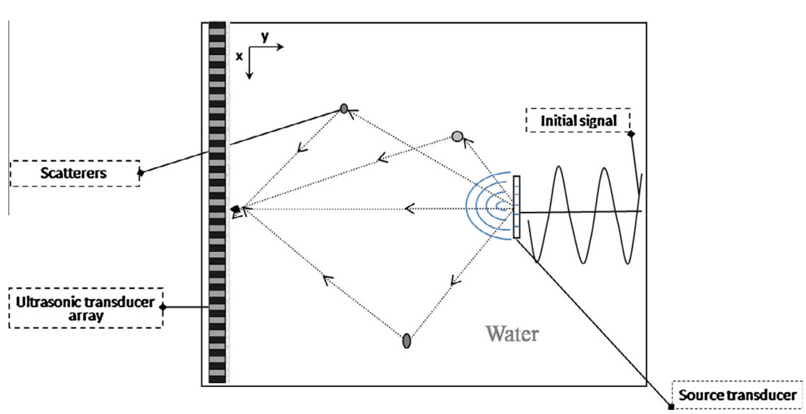

Fig. 1. Schematic of the simulated experimental setup.

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