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Selective focusing through target identification and experimental acoustic signature extraction: Numerical experiments

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ABSTRACT

Using transducer arrays and appropriate emission delays allow to focus acoustic waves at a chosen location in a medium. The focusing spatial accuracy depends on the accurate knowledge of its acoustic properties. When those properties are unknown, methods based on the Time-Reversal principle allow accurate focusing. Still, these methods are either intrusive (an active source has to be introduced at the target location first), either blind (the target cannot be selected in the presence of several objects.) The purpose of the present work is to achieve non-invasive accurate focusing on a selected target using inaccurate acoustic properties for the investigated medium. Potential applications are for instance non-invasive surgery based on High Intensity Focused Ultrasound (HIFU). Numerical experiments are presented and demonstrate accurate focusing on a previously designated target located in an unknown heterogeneous medium.

1. Introduction

Focusing ultrasonic waves in a given region of a fluid or a solid medium may be achieved for nondestructive purposes, such as for array-based imaging methods. Focusing ultrasounds increases the signal to noise ratio of the experimental data corresponding to the targeted region of the investigated medium. It thus enhances the image contrast (ability to see desired structure against the background) in this region. Focusing is also used for destructive purposes, especially for therapeutic applications. It is a popular method for kidney stone fragmentation since the 80s [1] and High-Intensity Focused Ultrasound (HiFU) are used for soft tissues necrosis by hyperthermia [2]. These methods allow localized non-invasive surgery. Still, the spatial accuracy of the focused beam has to be assured to prevent sane tissues to be damaged. Different focusing methods that are based on the use of a transducer array are compared in Table 1.

The method referred here as TOF (Time Of Flight) consists of considering a homogeneous medium and of computing the appropriate emission delays to be applied to each transducer of the array based on the distances between the transducers and the target. This is the most classical method. Its accuracy fully relies on the wave velocity estimation accuracy. In most experimental situations, the medium properties are not accurately known which leads to inaccurate focusing. For example, the human body is made of different soft tissues whose mechanical properties and thicknesses are patient-dependent. Furthermore, structures such as bones exhibit a strongly different wave propagation behavior. The TOF method can be enhanced with X-ray or MRI (Magnetic resonance imaging) image guidance. As an example, monitoring the temperature elevation with MRI allows to accurately locate the focusing region [3] and, if needed, to correct the delay laws applied to the array for more accurate focusing. Different solutions based on the Time-Reversal principle [4] were also proposed. They all rely on the acquisition or the estimation of the target acoustic signature. As a matter of fact, time-reversing this signature ensures the generated wave field to focus on the target. In Table 1, TR1 refers to the use of a Time Reversal Mirror method where the acoustic signature is obtained with an active source inserted at the target location. This method is applicable without any knowledge on the mechanical parameters of the medium. It was for instance applied to sheep brain surgery [5]. Still, the active source requirement makes the method intrusive as the source has to be

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Table 1
Comparison between wave focusing methods.

Method	TOF	TR1	TR2	DORT	SelF
Number of measurements before focusing	0	1	0	N_t	1
Accuracy dependency on medium knowledge	Full	None	Full	None	Low
Possible location of focusing spots	AW (Anywhere)	AW	AW	Biggest scatt.	AW
Intrusiveness	No	Yes	No	No	No

inserted at the target location. Transcranial focusing experiments were however achieved with a fully nonintrusive method [6] noted TR2 in Table 1. The experimental target signature measurement performed in TR1 is replaced by its numerical simulation in TR2. In order to compute the target signature, the medium has to be accurately known. In [6], the skull of the animal and its relevant mechanical properties were first measured with a CT scan (X-ray Computed Tomography). These data were exported to the simulation software and the target acoustic signature was computed. The DORT (French acronym for Decomposition of the time reversal operator) method allows to extract the signatures of the most echogenic scatterers both in a non intrusive way and without any knowledge of the medium [7]. It is based on a preliminary set of measurements that consist of firing one transducer at a time and in measuring the response of the investigated medium on all transducers. Defining N_t the number of transducers, N_t emission-acquisition are required. In the presence of several scatterers, their acoustic signatures can be extracted using DORT but each signature is hardly associated with the corresponding scatterer. Furthermore, only the most echogenic scatterers can be targeted [7]. The SelF (Selective Focusing) method proposed in this paper allows to select the target in an image and to perform accurate focusing even if the medium properties are not accurately known.

Basically, applying the SelF method first consist of a single emission-acquisition. Then, an image is computed based on the experimental data and the target is identified by an external user or a program. The image is then modified in a way that only the target remains in it. All other pixels are set to zero. Finally, an inversion procedure converts the modified image into corresponding acoustic signature. Time-reversing this signature ensures accurate focusing on the target. To easily achieve this inversion procedure, a specific imaging procedure is used: Fast Topological Imaging [8]. This imaging procedure ensures high resolution even with a single illumination and makes the inversion procedure efficient and easy to implement. The advantage of the SelF-EASE method (Selective Focusing through Experimental Acoustic Signature Extraction) is that even with inaccurate wave speeds and thus inaccurate target location in the image, the acoustic signatures extracted do correspond to the target in the experimental medium. The condition for its successful application is the target identification possibility. Thus, having an approximate knowledge of the homogeneous or heterogeneous medium is sufficient to perform accurate focusing.

First, the matrix formulation of FTIM is calculated in Section 2. This formulation allows the Experimental Acoustic Signature Extraction (EASE) procedure that is presented in Section 3. Three numerical experiments are then studied in Section 4. The first one consists of extracting the acoustic signature of a specific object in the presence of several other objects located nearby. Experiments #2 and #3 are performed in an heterogeneous medium mimicking a human breast immersed in water. Experiment #2 consists of extracting the acoustic signature of a small scatterer located in the breast whose mechanical properties are supposed unknown and of comparing Selective Focusing with classical Focusing assuming the same error on the medium properties knowledge. Experiment #3 consists of focusing wave in a large tumorous region identified by its interfaces with the sane tissues.

2. Matrix-formulation of fast topological imaging

Topological imaging methods derive from the application of topological optimization methods to inverse acoustic problems in the 2000s [9,10]. They have been applied to media inspected with a transducer array with nondispersive acoustic and elastic waves [8,11,12], with dispersive waves [13], with anisotropic waves [14] as well as to reverberant media [15]. All these applications rely on two simulations computed with a model of the investigated medium, the so called reference medium. For optimal results, the mechanical properties of the reference medium must be as close as possible to those of the investigated medium. Topological imaging highlights all the differences between the reference medium and the experimental medium. In what follows, only fluid media will be considered.

The two simulations computed in the reference medium respectively correspond to the direct and the adjoint problem. In the reference medium, emitters and receivers are located at the same locations as in the experiments. The direct problem consists of emitting waves in the same way as in the experiments and in computing the wave field. Assuming that the transfer function $H_i^e(\mathbf{M},\omega)$ between the pressure field in the reference medium at coordinates $\mathbf{M}$ and the normal velocity generated by emitter i is known for all angular frequencies ω, the pressure field solution of the direct problem is given by:

$$U(\mathbf{M},\omega) = \sum_i H_i^e(\mathbf{M},\omega)E_i(\omega) \tag{1}$$

where $E_i(\omega)$ is the velocity boundary condition corresponding to transducer i. The adjoint field consists of backpropagating the residue. The residue is defined as the difference at the receiver locations between the pressure field in the reference medium and that in the experimental medium. It thus corresponds to the acoustic signatures of the differences between reference and experimental media. Noting $\mathbf{M}_j^t$, the receiving transducer location, the residue is given by $U(\mathbf{M}_j^t,\omega) - R_j(\omega)$ where $R_j(\omega)$ is the pressure field measured by the receivers. As the time-domain backpropagation corresponds to the phase conjugation in the frequency domain, the solution of the adjoint problem is given by:

$$V(\mathbf{M},\omega) = \sum_j H_j^r(\mathbf{M},\omega)\Big(U(\mathbf{M}_j^t,\omega) - R_j(\omega)\Big)^* \tag{2}$$

where $H_j^r(\mathbf{M},\omega)$ is the transfer function of receiver j when used as an emitter.

When direct and adjoint fields are known, the topological gradient can be easily computed. Its exact formulation depends on the kind of inhomogeneity initially studied in the mathematical background of the method. Here, a more generic formulation is used defined by $G(\mathbf{M})$:

$$G(\mathbf{M}) = \sum_{\omega>0} U(\mathbf{M},\omega)V(\mathbf{M},\omega) \tag{3}$$

For the inversion procedure, we will use the complex topological gradient $G(\mathbf{M})$ and the imaging function is given by $|G(\mathbf{M})|$, according to the FTIM method. Thus, $G(\mathbf{M})$ is given by:

$$G(\mathbf{M}) = \sum_{\omega>0}\sum_i\sum_j H_i^e(\mathbf{M},\omega)E_i(\omega)H_j^r(\mathbf{M},\omega)\big(U(\mathbf{M}_j,\omega) - R_j(\omega)\big)^* \tag{4}$$

$G(\mathbf{M})$ is linearly dependent on the conjugated residue $\big(U(\mathbf{M}_j,\omega) - R_j(\omega)\big)^*$. The purpose of the matrix-approach is to write Eq. (4) as follows: