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Simulation study of a chaotic cavity transducer based virtual phased array used for focusing in the bulk of a solid material

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ABSTRACT

In acoustic and ultrasonic non-destructive testing techniques, it is sometimes beneficial to concentrate sound energy at a chosen location in space and at a specific instance in time, for example to improve the signal-to-noise ratio or activate the nonlinearity of damage features. Time Reversal (TR) techniques, taking advantage of the reversible character of the wave equation, are particularly suited to focus ultrasonic waves in time and space. The characteristics of the energy focusing in solid media using principles of time reversed acoustics are highly influenced by the nature and dimensions of the medium, the number of transducers and the length of the received signals. Usually, a large number of transducers enclosing the domain of interest is needed to improve the quality of the focusing. However, in the case of highly reverberant media, the number of transducers can be reduced to only one (single-channel TR). For focusing in a non-reverberant medium, which is impossible when using only one source, an adaptation of the single-channel reciprocal TR procedure has been recently suggested by means of a Chaotic Cavity Transducer (CCT), a single element transducer glued on a cavity of chaotic shape. In this paper, a CCT is used to focus elastic energy, at different times, in different points along a predefined line on the upper surface of a thick solid sample. Doing so, all focusing points can act as a virtual phased array transducer, allowing to focus in any point along the depth direction of the sample. This is impossible using conventional reciprocal TR, as you need to have access to all points in the bulk of the material for detecting signals to be used in the TR process. To asses and provide a better understanding of this concept, a numerical study has been developed, allowing to verify the basic concepts of the virtual phased array and to illustrate multi-component time reversal focusing in the bulk of a solid material.

1. Introduction

Time reversal (TR) techniques have become a vibrant topic of innovative research in ultrasonic applications [1–4]. The basic premise of time reversed acoustics (TRA) is that, if the wave field can be known as a function of time on some boundary surrounding a given region, then it can also be found at every point inside that region at previous times by using the wave equation with time running backwards. In other words, the result of a TR process is that the waves recorded on the boundary are focused back in space and time on the acoustic sources, or on the scattering targets inside the region which were acting as secondary sources. Doing so, it enables us to locate strong scatterers (e.g. inclusions and interfaces with high impedance contrast) which are hidden inside a region. Applications of TRA can be found in seismology (earthquake localization) [5–8], diagnostic and therapeutic medicine [9–12], and in non-destructive testing [13–20].

In a classical TRA experiment, waves generated by an acoustic source are first measured by an array of piezoelectric transducers located around the source, and then time reversed and re-emitted by the same transducers array. The created time reversed wave then propagates back and eventually focuses on the location of the initial source, now remaining passive. The quality of the focusing can be improved if the transducers cover a closed surface around the medium such that information is obtained from all wave fronts propagating in any possible direction [21]. In practice, however, this is difficult to realize and the TR operation is usually performed on a limited angular area, reducing the reversal focusing quality.

An important advantage of TRA for engineering materials is that it works extremely well in heterogeneous media (actually better

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than in homogeneous ones). Multiple scattering in transmission experiments [22] or multiple reflections in wave guides [23–26] or inside chaotic cavities [27–29], instead of being a hindrance, actually improve the focusing. This reduces the number of receivers needed to obtain a good reversal quality. Draeger et al. [27–29] and Fink et al. [30] even proved the possibility of reducing the number of elements down to one by using multiple reflections inside a closed chaotic cavity. In addition, it was shown that the focusing quality can be increased by a longer recording of the time reversed signal [27]. However, for too long time windows, the focusing quality can no more be improved, since the essential signal information can no longer be discerned from noise due to attenuation in the material.

In standard single-channel TR experiments, a signal measured by the receiver is time reversed and subsequently re-emitted back into the medium by a transducer located at the same position as the receiver, resulting in a focusing at the original source position [8]. Due to reciprocity in acoustic and elastic wave propagation, the back propagation of the time reversed signal from the position of the original source to the position of the corresponding receiver will result in a focus of energy at the actual receiver location [31]. This procedure is called reciprocal TR. Implementation of reciprocal TR thus allows to selectively focus acoustic/elastic energy at any position in a given medium, provided the direct received signal can be predicted or obtained at that position, for instance by an appropriate material model or – for surface locations – by recording the signal using a laser vibrometer or a non-contact transducer. In a number of studies, the reciprocal TR technique has been used to focus a large amount of energy at a certain position in order to trigger nonlinear features at that location [14,15,32].

In case of a non-reverberant sample, the above described TR technique cannot be used anymore, since the absence of reflections implies that the only information path between the source and the receiver is the direct path. For an accurate re-focusing of the energy multiple information paths coming from different directions (i.e. originating at different virtual source locations) are required. Recently, a solution for this problem was proposed using a Chaotic Cavity Transducer (CCT), consisting of a transducer glued to a cavity of chaotic shape, which itself is placed in or connected to a non-reverberant medium. The principle of a CCT was originally introduced for 3D imaging in fluids [33–37] and was later extended to applications dealing with elastic waves in solids. Van Damme et al. [38] experimentally investigated the use of a CCT for elastic imaging in reverberant and non-reverberant solid media. Choi et al. [39] described the construction of a CCT based 2D virtual array used for pulse-echo type non-destructive inspection of solid materials. In this paper, we also discuss a CCT based virtual array using a finite element based model developed in the commercially available software package Comsol Multiphysics. However, other than the ultrasonic 3D imaging described by Choi et al., we will use the virtual phased array to focus elastic energy at a predefined location in the bulk of a solid material. This is of great importance, as such a TR focusing cannot be obtained using conventional reciprocal TR since we do not have access to points in the bulk of the material to detect the signals to be used in the TR process. Virtual experiments will be performed, verifying and illustrating this innovative concept. In future, the numerical model can be modified and extended to help in the further development and optimization of linear and nonlinear imaging techniques based on TR principles.

2. Time reversal modeling approach

To demonstrate the feasibility and usefulness of single-channel reciprocal TR techniques using a chaotic cavity transducer, we exploit a fully numerical approach that covers the emission of a virtual sound wave from the source location, the recording of the forward wave propagation signal (single or multiple components) at a particular receiver position, the back propagation of the time reversed signal(s) from the original location of the emitter and the analysis of the energy focusing quality at the considered receiver location. In traditional TR experiments, the source signal consists of a short pulse, which is applied to the transducer. To obtain spatial and temporal focusing, the impulse response of this signal, measured by the receiver, is time reversed and broadcasted back into the medium. It is shown, however, that the quality of the focusing can be improved by (1) applying a pulse compression technique, which involves the use of a linear sweep signal (also known as chirp) as excitation signal instead of a short pulse [38,40–42] and (2) by utilizing a deconvolution, or inverse filtering, technique [43]. In the present simulations, a combination of both is used. Since the simulations represent wave propagation phenomena in a supposedly linear medium, the finite element model used for the TR simulations is solved in frequency domain. Moreover, taking advantage of the spectral method, one can obtain the exact same solution of the model without performing two separate simulations (i.e. one for the forward propagation and one for the back propagation phase).

The model is first solved for a discrete number of frequencies using a constant amplitude equal to one as an input for the boundary condition at the source. This input actually corresponds to the Fourier Transform (FFT) of an impulse. For every frequency, the complex valued amplitudes calculated in each point of the model are then stored. These stored solutions are corresponding to the impulse responses, or the Green functions $G_i(\omega)$, at each position, where index i denotes a particular position. The complex valued signals $R_i(\omega)$, recorded in response to a linear swept signal $S(\omega)$ (or rather from the FFT of $S(t)$), can then be calculated as follows:

$$R_i(\omega) = G_i(\omega) \cdot S(\omega).$$

For the back propagation of a particular recorded signal $R_j(\omega)$ $(i = j)$, we first apply pulse compression by performing a point-wise multiplication of the complex conjugate of the linear swept signal $S(\omega)$ and the recorded signal $R_j(\omega)$. Subsequently, inverse filtering is applied by dividing the obtained signal by the square of the norm of $R_j(\omega)$ (i.e. $|R_j(\omega)|^2$). As such, we get the following transformation:

$$R_j(\omega) \rightarrow \frac{R_j(\omega) \cdot S^*(\omega)}{|R_j(\omega)|^2 + \epsilon_j},$$

where $*$ denotes the complex conjugate operation and ϵ_j is a constant added to the denominator to ensure that we never divide by zero. The constant is related to the original received signal as follows [43]:

$$\epsilon_j = 0.9\ \mathrm{mean}(|R_j(\omega)|^2).$$

Finally, the focusing signals $F_i(\omega)$ are calculated by multiplying – frequency by frequency – the Green functions $G_i(\omega)$ by the complex conjugate of the obtained signal (i.e. the FFT of the time reversed signal after pulse compression and inverse filtering):

$$F_i(\omega) = G_i(\omega) \cdot \left(\frac{R_j(\omega) \cdot S^*(\omega)}{|R_j(\omega)|^2 + \epsilon_j} \right)^*. \tag{1}$$

One can easily see, that for $i = j$ (i.e. the position where the direct received signal was obtained), the focusing signal becomes:

$$F_j(\omega) = \frac{|R_j(\omega)|^2}{|R_j(\omega)|^2 + \epsilon_j} \approx 1,$$

which approximates the spectrum of a delta function $\delta(t)$.