REAL TIME INVERSE FILTER FOCUSING THROUGH ITERATIVE TIME REVERSAL

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Abstract

In order to achieve an optimal focusing through heterogeneous media we need to build the inverse filter of the propagation operator. Time-reversal is an easy and robust way to achieve such an inverse filter in non dissipative media. However, as soon as losses appear in the medium, time-reversal is not equivalent to the inverse filter any more. Consequently, it does not produce the optimal focusing and beam degradations may appear. In such cases, we showed in previous works that the optimal focusing can be recovered by using the so called spatio-temporal inverse filter technique. This process requires the presence of a complete set of receivers inside the medium. It allows to reach the optimal focusing even in extreme situations such as ultrasonic focusing through human skull or audible sound focusing in strongly reverberant rooms. But, this technique is time consuming and implied fastidious numerical calculations. We propose here a new way to process this inverse filter focusing technique in real time and without any calculation.

Introduction

The basic process in most acoustic applications is to focus a sound or ultrasound beam through an unknown medium Time reversal [1] us a method to focus through complex media. The method is based on the time reversal invariance of the wave equation in a non dissipative medium. A wave diverging from a punctual source and received by a set of transducers enclosing the medium can be time-reversed and reemitted by the elements. The generated wave will converge back to its original source location as if time was running backwards. In this case, we can imagine that the time reversal process acts as an inverse filter of the diffraction process.

Unfortunately, there are two problems that degrade the time reversal focusing and do not permit to achieve an inverse filter focusing. First, dissipation breaks the time reversal invariance of the wave equation. A wave will suffer twice the dissipation effects during its forward and backward propagation and this irreversibility degrades the time reversal focusing quality. Secondly, a time reversal close cavity is difficult to build and in practice, the time reversal operation is achieved on a limited aperture known as a time reversal mirror. This angular aperture limitation gives rise to new information losses that may cause the focusing quality to decrease, particularly in strongly diffracting media.

In order to correct these problems, it is possible to calculate an *explicite* spatio-temporal inverse filter of the propagation by embedding a set of receivers (control points) inside the propagation medium and acquiring experimentally all the impulse responses relating each element of the array to each control point [2]. After the experimental acquisition of this propagation operator we can compute a numerical inversion and deduce the set of optimal focusing signals. In a strongly dissipative medium the results given by this technique are better than the results achieved with a time reversal process [3], but the time needed to acquire the operator and compute its numerical inversion is very long.. Here, we propose a new method which allows to recover the inverse filter focusing using an iterative time reversal process. This iterative process may be implemented in real-time as it introduces very simple operations and does not require to acquire all the propagation operator relating the array to the control points. Here, the numerical inversion is replaced by an "experimental inversion" achieved by successive wavefield propagation in the medium.

The iterative method

The experimental configuration consists in an *emitting* array of transducers and a *control* array inside the propagation medium. Both arrays (*emitting* and *control*) consist in transducers which are able to work in transmitting and receiving mode. The medium is considered as heterogeneous and dissipative (see figure 1).

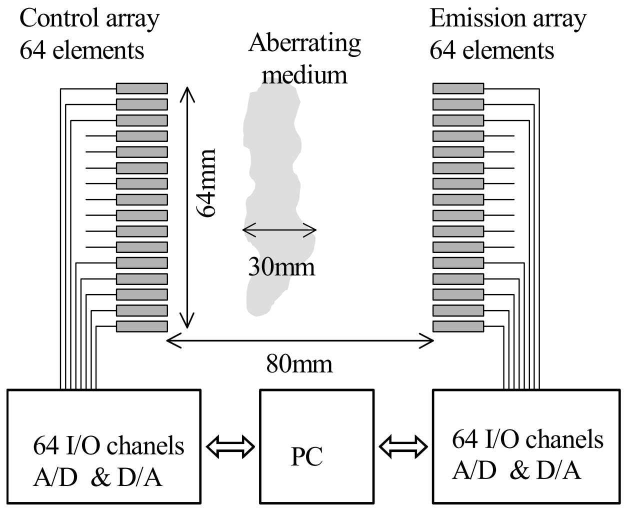

Figure 1. Experimental setup

Our objective is to focus a sharp pulse over the mth transducer of the control array and 0 over all the other transducers. We can write this objective like a vector of signals $o(t) = [0,\ldots, 0, o_m(t),0,\ldots,0]$, where $o_m(t)$ is a sharp signal. The focusing of this signal is done in this sequence:

- The first step of the process consists in transmitting the time reversed signal $o(-t)$ from the *control* array. After propagation through the medium, the resulting wavefront $e_1(t)$ is recorded on the *emitting* array (see Figure 2.a).
- In a second step, these signals are time-reversed and $e_1(-t)$ is re-transmitted by the *emitting* array. As one can notice, the description below corresponds to a classical time reversal experiment. However, in a dissipative medium, time reversal is not optimal and the focusing pattern $r_1(t)$ recorded on the *control* array is not exactly the objective $o(t)$ and it has large sidelobes (fig 2.b).
- In order to recover an optimal focusing, a third step is introduced. The difference between the focusing pattern $r_1(t)$ and the desired spatio-temporal objective $o(t)$ is then computed. This difference $d(t) = o_1(t)\text{-}r(t)$ is time-reversed and transmitted by the *control* array. After propagation through the medium, a wave $c(t)$ is received and recorded on the *emitting* array . If we re-transmit this signal $c(-t)$ by the *emitting* array, we should obtain on the control array a quite good approximation of the sidelobes $d(t)$.
- $c(t)$ can be considered as a correction signal to improve the focusing pattern. Thus, by transmitting the corrected set of signals $e_2(t) = e_1(t) + c(t)$ on the *emitting* array, we will obtain in the *control* array a new focusing $r_2(t)$ that approaches in a better way the focusing objective.

This process can be repeated iteratively up to the attainment of the optimal focusing.

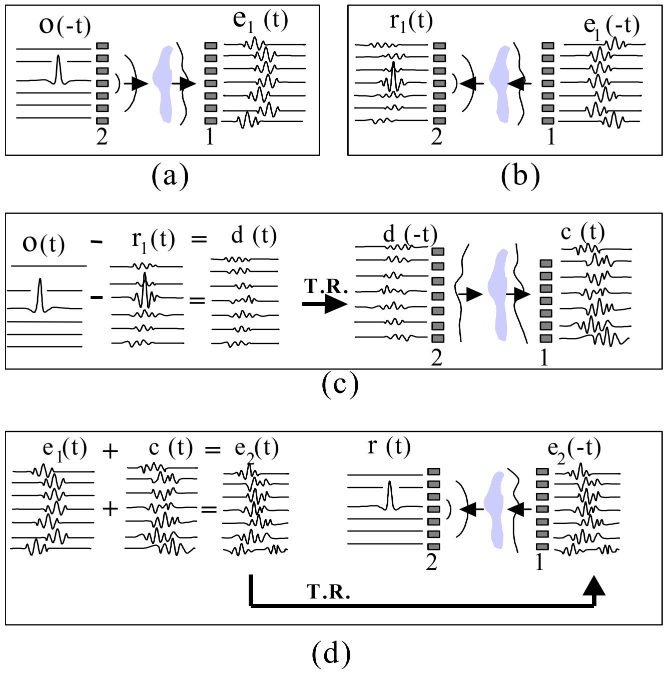

Figure 2. The iterative method. a) Emission of the objective pattern, b) Focusing by Time-reversal process, c) Emission of the difference wavefield , d) Focusing with new the corrected signals.

In figure 3 we can see an experimental focusing through an aberrating and dissipative medium using time reversal and using this iterative process. After the iteration, the spatio temporal lobes decrease in roughly 20 db.

Due to the simplicity of all these operations (emission, reception, time reversal, signal subtraction), this iteration can be implemented with a very high speed allowing a real time correction of the aberrations of the medium while focusing on each control point.

Figure 4 shows the evolution of the measured focusing pattern in the *control* array for different number of iterations. The case of a single iteration is the result of the standard time reversal technique. Due to the strong aberration of the medium the sidelobes are very high, nearly 10dB. After some iterations these sidelobes are cleared off and 30 iterations are here enough to reach a saturation in the focusing quality. The improvement of the focusing pattern between the first and the last iteration is extremely important. The resolution is improved by a factor 2 and the sidelobes level is reduced in nearly 15dB.

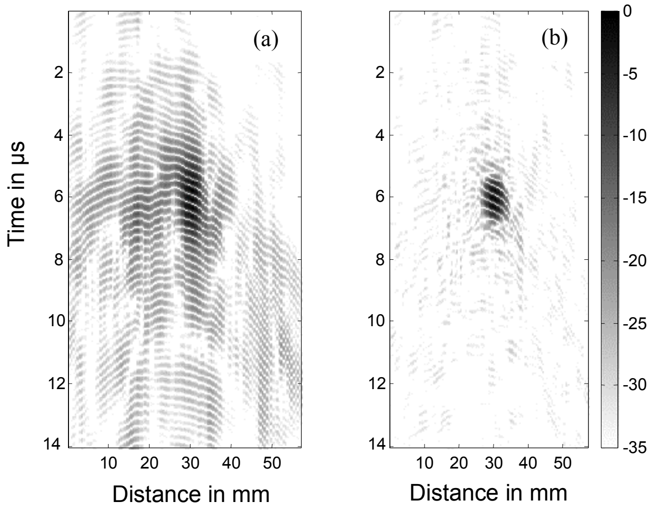

Figure 3. Spatio-temporal representation of the focusing achieved through an aberrating mask. a) with time-reversal, b) after 20 iterations of correction.

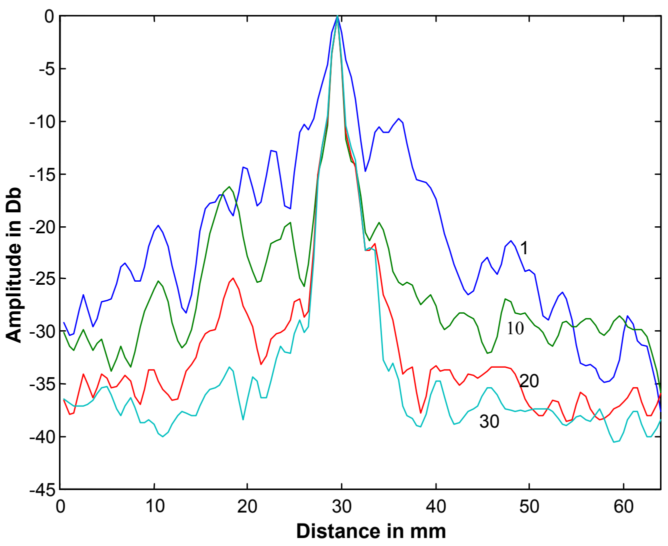

Figure 4. Spatial distribution of the focal spot with 1, 10, 20, and 30 iterations

Figure 5 compares this result with the direct inversion of the propagation matrix and with the classical time reversal process. The spatio-temporal inverse filter and the iterative method give the same focusing quality. On the other hand, due to the heterogeneous absorption induced during the propagation through the aberrating medium, the time reversal process does not give good results. The difficulty in focusing through such an aberrating medium is demonstrated in the same figure by the focusing pattern achieved with a classical cylindrical time delay law (i.e. assuming a constant speed of sound in the medium). As one can notice, the cylindrical law is not able to focus on the correct point and the sidelobes level is very high, of about -5dB.

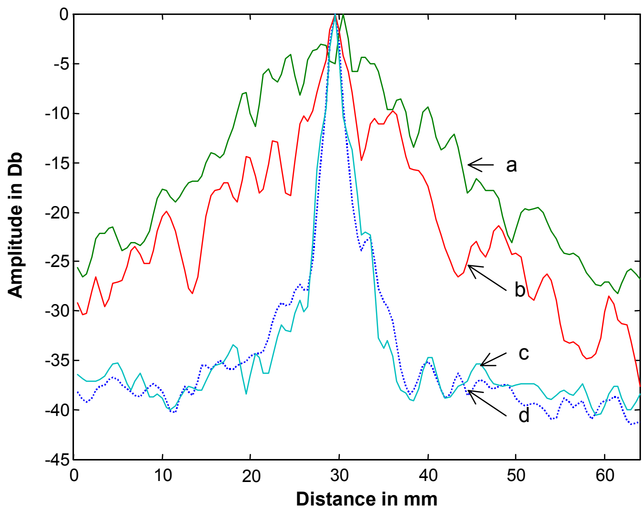

Figure 5. Focusing patterns obtained by, a) classical Cylindrical time delay focusing law, b) Time reversal processing, c) Iterative time reversal processing, d) spatio-temporal inverse filter

Conclusion

A new real time method for optimal focusing through absorbing and complex media was presented. This method iterates the time-reversal process in order to cancel the focusing beam degradation due to absorption and other information losses. Contrary to numerical inverse filtering, this iterative technique does not require any computation and it achieves the inverse filter in an experimental way using wave propagation instead of computer power. This iteration may be implemented at real-time and it has a lot of potential applications in imaging and communications. Experimentally, we have proved the efficiency of the iteration in an absorbing and aberrating medium and its results are very close to those of the inverse filter. We think that this method may be very useful to focus in complex media that change slowly in time. In this case, the inverse filter is not capable of focusing because while the whole propagation operator is recorded and inverted the medium changes. As the time of one iteration is of the order of the propagation time, we can correct the focusing continuously with a few iterations starting each correction with the last focusing.

References

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[3] J.-F. Aubry, M. Tanter, J. Gerber, J.-L. Thomas, M. Fink. "Optimal focusing by spatio-temporal inverse filter : Part II. Experiments" *Journal of Acoustical Society of America*, Vol. 101,pp 48-58, July 2001.