Time Reversal of Ultrasonic Waves through Phononic Crystals

François Van Der Biest, Gillian Boccara, Arnaud Tourin, Mathias Fink
Laboratoire Ondes et Acoustique, ESPCI, 10 Rue Vauquelin, 75005 Paris, France

Introduction

Phonic band gap crystals are periodic structures, analogous to photonic crystals for electromagnetic waves, that forbid propagation of acoustic waves for a certain range of frequencies. We present here time-reversal experiments performed through 2D phononic crystals. Inside the stop band, no propagating mode exists but tunneling (see Ref. [1]) and evanescent waves are involved. Both time compression and spatial focusing are quantified.

Phononic Crystals

The periodic samples we use for these experiments are made of steel rods immersed in water. The lattice is square and the distance between two adjacent rods is 1.5 mm. The sample is made of eight rows, each containing one hundred rods. The diameter of each rod is 0.8 mm. Such a crystal exhibits a stop band with a central frequency of 485 kHz in the [10] direction. This is not a true band gap since the attenuations in both major cristallographic directions do not overlap. The sample can easily be characterized using the well-known impulse response technique. Using a transducer with a central frequency of 500 kHz, we send a short pulse into such a crystal, and we record the transmitted wave. The same process must be repeated through water to get the reference pulse. We easily deduce the transmission factor (Fig. 1), as well as phase and group velocities.

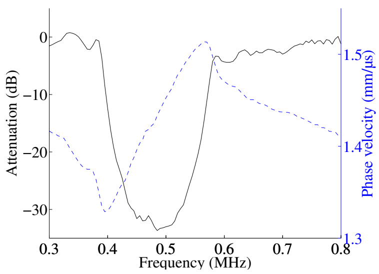

Figure 1: Attenuation (black) and phase velocity (blue) through a 8-row sample. Maximum attenuation (33 dB) occurs at 485 kHz, while the gap width is 185 kHz at -6 dB. Anomalous dispersion characterizes the gap [397-568 kHz].

In the following section, we present Time Reversal experiments through the phononic crystal as well as in water and through a 37 mm thick disordered sample, also an arrangement of rods.

Time Reversal

Why is it interesting to experiment Time Reversal through phononic bandgaps ?

The idea behind such an experiment is the following: it has been shown (Ref. [2]) that the SNR of the spatio-temporal compression achieved by TR is in fact sensitive to the number of frequency information grains, that is, the ratio of the available bandwidth on the width of the autocorrelation function of the transmitted signal. When frequencies are removed from the spectrum by the sample, focusing quality should decrease.

Experimental setup

In the experiment, two motorized 500 kHz monoelements were used to acquire the propagation matrix. Their positions were independently computer controlled, one to fire short signals at position i, the other receiving at position j behind the sample. Spatial sampling is lambda.

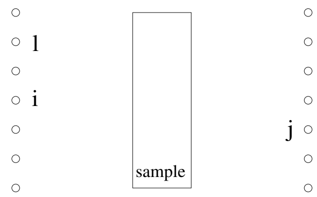

Figure 2: Experimental setup.

We note h_{ij} the impulse response between positions i and j. To reconstruct the time reversal compression at position l when i was firing, we compute correlations between the recorded signals :

$$S_l(t) = \sum_j h_{ij}(T-t) \otimes h_{jl}(t) \quad (1)$$

Taking into account reciprocity of the propagation medium, this can be determined with the propagation matrix previously acquired, since $h_{jl}(t) = h_{lj}(t)$.

Spatial focusing

Classical results for Time Reversal (TR) through heterogeneous media without absorption show an hyper-resolution (Ref. [2]), which means that the beam width around the source is several times finer with a multiple scattering sample than in water. Indeed, in the learning stage of TR, due to the position of the multiple scattering (MS) sample and to the limited size of the receiving array, high spatial frequencies that are lost during the propagation in water are collected by the sample and reradiated at its output. A multiple scattering sample plus a Time Reversal Mirror (TRM) can be seen as an acoustic lens whose aperture is bigger than the aperture of the TRM alone. It has also been shown (Ref. [2]) that resolution through a MS sample in a TR experiment is independant of the number of transducers emitting the time reversed wave. These classical results are well retrieved in our experiments, as shown in Fig. 3.

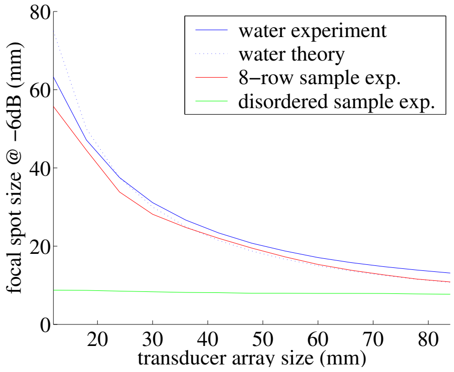

Figure 3: TR focal spot width around the source as a function of the number of transducers attending time reversal for different samples (water, 8-row periodic, disordered).

When the number of transducers attending TR is increased, the -6 dB resolution through a disordered sample is relatively constant, at levels well under the resolution of TR through water. The surprising news is that there is no noticeable hyper-resolution through a periodic 8-row sample. Why ? First of all, many incident wave vectors corresponding to the stop bands are trapped by the sample. Secondly, forward scattering dominates and creates retarded replicas of the illumination front. Thus, the high spatial frequencies are not efficiently redirected in the TRM aperture. This is in accordance with previous simulations (Ref. [3]), where the rows of the periodic sample were replaced by thin steel layers immersed in water. The whole 1D system, computed with acoustic impedances, showed great concordance with the experimental results.

Time compression

As expected, time compression through the 8-row periodic sample does not provide a good SNR: 6 dB vs. 18 dB through a disordered sample (Fig. 4). This is mainly due to the strong attenuation of frequencies in the range of the gap.

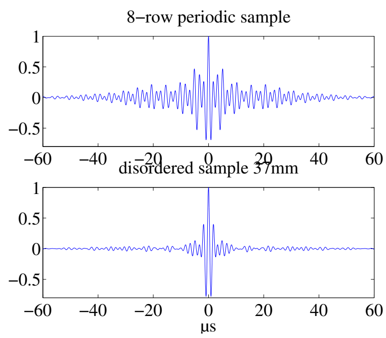

Figure 4: Time compression through a periodic 8-row sample (top) offers 6 dB SNR and through a 37 mm thick disordered sample, 18 dB SNR (bottom).

Time Reversal in the Band Gap

Let's focus now on TR of gaussian wave packets whose frequencies lie right in the gap. To that goal, we digitally filtered the impulse responses with a 80 kHz FWHM gaussian filter centered at 485 kHz before time reversing them. Since waves are not totally reflected by the phononic bandgap material, there is still a small transmitted part which comes from the conversion of evanescent waves into propagative waves at the ouput of the sample. This part can be recorded, thus time reversed. Although these waves undergo twice the attenuation in the phononic crystal, they however refocus at the point source, as seen in Fig. 5.

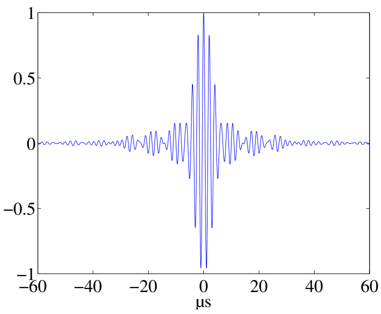

Figure 5: Temporal compression at focal spot through a 8-row sample for a gaussian wave packet in the gap. SNR is 16 dB.

The surprise comes from the SNR of such a temporal compression which is comparable to the SNR inside the 37 mm thick disordered sample (Fig. 4). It is our opinion that such a quality for temporal focusing can be achieved because of the relative homogeneity of transmission in the frequency domain 485 kHz ± 40 kHz. This kind of focusing is done at the expense of spatial quality : spatial lobes appear at 8 dB below the peak.

Conclusion

To our knowledge, this is the first time that TR of evanescent waves is experimentally studied in acoustics. This subject involves interesting features such as reversibility of evanescent waves, that was studied by Carminati (Ref. [4]), but also sheds new light on the limitations of Time Reversal.

References

[1] Yang *et al.*, Ultrasound Tunneling through 3D Phononic Crystals, Phys. Rev. Lett, **88** (2002), 104301.

[2] Derode *et al.*, Random Multiple Scattering of Sound, II. Is Time Reversal a self averaging process ?, Phys. Rev. E, **64** (2001), 036606.

[3] Van Der Biest *et al.*, Study of a "Fabry-Pérot" structure consisting of two phononic crystals, WCU 2003 proceedings.

[4] Carminati *et al.*, Reciprocity of evanescent electromagnetic waves, JOSA A, **15**, No.3, (1998).