

## TIME REVERSAL MIRRORS

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### ABSTRACT

The objective of this paper is to show that time-reversal invariance can be exploited in acoustics to accurately control wave propagation through complex media and create a variety of useful instruments. To illustrate the robustness of time reversal mirrors, several experiments conducted in multiply scattering media, in waveguides and in reverberant cavities are presented. They show that, contrary to long-held beliefs, multipathing and multiple scattering enhances resolution in time reversal focusing, by making the effective size of the time reversal mirror much larger than its physical size. Applications of time-reversal mirrors in various fields will be discussed.

The acoustic and the elastic wave equation in a non-dissipative heterogeneous medium are both invariant under a time reversal operation. Indeed, it contains only a second-order time-derivative operator. Therefore, for every burst of sound (or ultrasound) diverging from a source- and possibly reflected, refracted or scattered by any heterogeneous media- there exists in theory a set of waves that precisely retraces all of these complex paths and converges in synchrony, at the original source, as if time were going backwards. This idea gives the basis of time-reversal acoustics. These concepts are not only very interesting physical phenomena themselves, but also possess the possibility of wide range application. In particular, their applications to focus a wave through an inhomogeneous medium, is very attractive and many applications in medical therapy, non-destructive testing, underwater telecommunications, detection, man machine interface are under development.

Taking advantage of these two properties the concept of time reversal mirror (TRM) has been developed and several devices have been built which illustrated the efficiency of this concept [1,2]. In such a device, an acoustic source, located inside an heterogeneous lossless medium, radiates a brief transient pulse that propagates and is distorted by the medium. If the acoustic field can be measured on every point of a closed surface surrounding the medium (acoustic retina), and retransmitted through the medium in a time-reversed chronology, then the wave will travel back to its source and recover its original shape. From an experimental point of view a TRM consists of a two-dimensional piezoelectric transducer array that samples the wavefield over a closed surface. An array pitch of the order of  $\lambda/2$  where  $\lambda$  is the smallest wavelength of the pressure field is needed to insure the recording of all the information on the wavefield. Each transducer is connected to its own electronic circuitry that consists of a receiving amplifier, an A/D converter, a storage memory and a programmable transmitter able to synthesize a time-reversed version of

the stored signal. In practice, closed TRMs are difficult to realize and the TR operation is usually performed on a limited angular area, thus limiting reversal and focusing quality. A TRM consists typically of some elements, or time-reversal channels.

The basic principle of a TRM is an extension for broadband pulsed waves to the optical phase conjugated mirror designed for quasi monochromatic waves. However, this equivalence is only valid mathematically and there are some fundamental differences between these two techniques.

One very interesting property of TRM is that the number of time-reversal channels needed to insure a good refocusing on the source decreases if the wave traverses a multiply scattering or reverberating medium before arriving on the transducer array. Through media with high order multiple scattering, the large length of paths involved in the experiment widens the effective focusing aperture. After the time-reversal operation, the whole multiply scattering or reflecting medium behaves as a coherent focusing source, with a large angular aperture for enhanced resolution. As a consequence, in complex media, one is able to reduce the size and the complexity of the TRM. The same kind of improvement may be obtained for waves propagating in waveguides or in closed reflecting cavities. Multiple reflections along the medium boundaries significantly increase the apparent aperture of the TRM and a set of experiments conducted in waveguides and in cavities are presented. Acoustic tactile objects based on this principle have been developed that used the elastic wave radiated by the finger impinging on a solid object to localize the impact.

### TARGET DETECTION WITH TIME-REVERSAL TECHNIQUES

In many applications, such as NDT or SONAR techniques, one has to work in pulse echo mode and the sources are no more active, like in the experiments described earlier, but passive reflecting targets like defects.

For this purpose, a TRM array may be used in the following three-step sequence [3,4,5]. One part of the array generates a brief ultrasonic pulse to illuminate the region of interest in the solid. If the region contains a reflector, the reflected wavefront is converted by all the transducers of the array in electrical signals that are recorded. Then a time window is used to select the signals that are time-reversed and stored in electronic memories. The time-reversed signals are then transmitted to the transducers that emit an ultrasonic wavefront that refocuses exactly on the target through the interfaces. This process also compensates unknown deformation of the array. When the medium contains several targets, the problem is more complex and iteration of the TR

operation may be used to select one target. If, for example, the medium contains two defects of different reflectivity, time reversal of the echoes from these targets generates two wavefronts focused on each defect. The mirror produces the real acoustic images of the two reflectors on themselves. The higher-amplitude wavefront illuminates the most reflective target, while the weaker wavefront illuminates the second target. In this case, the time reversal process can be iterated. After the first time-reversed illumination, the weaker target is illuminated more weakly and reflects a fainter wavefront than the one coming from the strongest target. After several iterations, the process converges and produces a wavefront focused on the most reflective target only. It will converge if the separation between targets is sufficient to avoid the illumination of one target by the real image of the other one. Once the target is selected by the TRM, an image of the defect can be made by electronically tilting the last iterated wavefront in order to scan the zone surrounding the defect. Indeed there is a small angular aperture around the target (identical to the isoplanetic angle in astronomy) where a tilted wavefront keeps its focusing capability.

## CONCLUSION

Because acoustic TR technology is now easily accessible to modern electronic technology, many applications of time-reversal techniques are under development going from medical imaging, ultrasonic therapy, underwater acoustics, NDT, man machine interface.

## REFERENCES

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