Ultrasonic Time Reversal Mirrors

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Abstract. For more than ten years, time reversal techniques have been developed in many different fields of applications including detection of defects in solids, underwater acoustics, room acoustics and also ultrasound medical imaging and therapy. The essential property that makes time reversed acoustics possible is that the underlying physical process of wave propagation would be unchanged if time were reversed. In a non dissipative medium, the equations governing the waves guarantee that for every burst of sound that diverges from a source there exists in theory a set of waves that would precisely retrace the path of the sound back to the source. If the source is pointlike, this allows focusing back on the source whatever the medium complexity. For this reason, time reversal represents a very powerful adaptive focusing technique for complex media The generation of this reconverging wave can be achieved by using Time Reversal Mirrors (TRM). It is made of arrays of ultrasonic reversible piezoelectric transducers that can record the wavefield coming from the sources and send back its time-reversed version in the medium. It relies on the use of fully programmable multi-channel electronics. In this paper we present some applications of iterative time reversal mirrors to target detection in medical applications.

THE TIME REVERSAL MIRROR IN PULSE ECHO MODE

One of the most promising areas for the application of TRMs is pulse-echo detection. In this domain, one is interested in detection, imaging and sometimes destruction of passive reflecting targets. A set of transducers first sends a short impulse and then detects the various echoes from the targets. One looks for calcifications, kidney or gallbladder stones, or tumors. As the acoustic detection quality depends on the availability of the sharpest possible ultrasonic beams to scan the medium of interest, the presence of an aberrating medium between the targets and the transducers can drastically change both the beam profiles and the detection capability. In medical imaging, a fat layer of varying thickness, bone tissues, or some muscular tissues may greatly degrade focusing.

For such applications, a TRM array can be controlled according to a three step sequence. One part of the array generates a brief pulse to illuminate the region of interest through any aberrating medium. If the region contains a point reflector, the reflected wavefront is selected by means of a temporal window and then the acquired information is time-reversed and reemitted. The reemitted wavefront refocuses on the target through the medium. It compensates also for unknown deformation of the mirror array. Although this self-focusing technique is highly effective, it requires the presence of a reflecting target in the medium [1].

In media containing several targets, the problem is more complicated and iterations of the TR operation may be used to select one target. Indeed, if the medium contains two targets of different reflectivities, the time-reversal of the echoes reflected from these targets generates two wavefronts focused on each target. The mirror produces the real acoustic images of the two reflectors on themselves. The highest amplitude wavefront illuminates the most reflective target, while the weakest wavefront illuminates the second target. In this case, the time-reversal process can be iterated. After the first time-reversed illumination, the weakest target is illuminated more weakly and reflects a fainter wavefront than the one coming from the strongest target. After some iterations, the process converges and produces a wavefront focused on the most reflective target. It converges if the target separation is sufficient to avoid the illumination of one target by the real acoustic image of the other one [2].

Application to lithotripsy

The method of choice to treat kidney and gall stones involves the use of large amplitude acoustic shock waves that are generated extracorporeally and focused onto a stone within the body. Lithotripters typically have a high focusing gain so that pressures are high at the stone but substantially lower in the surrounding tissue. The alignment of stone in the patient with the lithotripter focus is accomplished with fluoroscopy or ultrasonic imaging. Focusing is achieved geometrically, i.e., with ellipsoidal reflectors, concave focusing arrays of piezoelectric transducers, or acoustic lenses. Shock waves have amplitudes at the focus on the order of 1.000 bar and a duration of a few microseconds. They are typically fired at a 1 s pulse repetition rate [3,4]. The main problem to overcome in the field of lithotripsy is related to stone motion due to breathing. Indeed, the lateral dimension of the shock wave in current lithotripsy devices is less than 5 mm and the amplitude of the stone displacement can reach up to 20 mm from the initial position. Hence, in classical focusing technique, shock waves often miss the stone and subject neighboring tissues to unnecessary shocks that may cause local bleeding.

Different approaches have been investigated to overcome these limitations. Most of them are based on a trigger of the high power pulses when the stone goes through the focus of the shock wave generator. These approaches may reduce the number of shots needed to disintegrate the stone but increase considerably the time of treatment. The use of 2D arrays of piezoelectric transducers has opened the possibility of electronic steering and focusing the beam in biological tissues and a time-reversal piezoelectric generator has been developed [5] to move electronically the focus and track the stone during a lithotripsy treatment.

The goal is to locate and focus on a given reflecting target among others, for example, a stone in its surroundings: others stones and organ walls. Moreover, the stone is not a point like reflector but has dimensions up to ten times the wavelength. In the basic procedure that has been developed, the region of interest is first insonified by the transducer array. The reflected field is sensed on the whole array, time-reversed and retransmitted. As the process is iterated, the ultrasonic beam selects the target with the highest reflectivity. If the target is spatially extended, the process converges on one spot, whose dimensions depend only on geometry of the time-reversal mirror and the wavelength. High amplification during the last iteration can be used to produce a shock wave for stone destruction. However, two problems limit this technique. For human applications, it is necessary to use very short high power signals (bipolar and unipolar pulses) to prevent damages caused in the organs by cavitational gas bubbles, while the iterated pulses have long duration. Besides, a complete time-reversal electronic is expensive and the number of time-reversal channels must be limited. To solve these problems, another procedure has been developed. In the first step, only a subgroup of the array is used in a time-reversed mode. This step is conducted with low power ultrasound in order to remain in linear acoustics. After some iterations, a low power ultrasonic beam, generated by the array subgroup, is focused on the stone. The last set of received signals is used to deduce a time of flight profile on the subgroup. This time of flight profile is then interpolated to the whole array. The final step consists in the generation, by the whole array, of very short high power signals with the correct delays.

Different time reversal mirrors have been designed for lithotripsy. They use bidimensional transducer arrays working at a central frequency of 360 kHz, made of 121 prefocused piezoelectric transducer elements arranged on a spherical cup of 190 mm radius of curvature

Multiple target detection

Iterative time reversal technique is well adapted to focus on the target of higher reflectivity. However, in many cases it is also interesting to learn how to focus on the other reflectors. In order to achieve selective detection and focusing on each reflector inside an unknown multitarget medium, a matrix formalism approach, that extended time reversal analysis, was developed by Prada et al [6,7,8]. This method is derived from the theoretical analysis of iterative TRM and consists at the construction of the invariant of the time reversal process. This analysis consists at determining the possible transmitted waveforms that are invariant under the time reversal process. For these waveforms an iteration of the time reversal operation gives stationary results. Such waveforms can be determined through the calculation of the eigenvectors of the so called time reversal operator. Indeed, the echoes of a single target are an eigenvector of the time reversal operator K*K, where K=K(?) represents the inter-element response matrix.

Using this basic idea that each target is associated to an eigenvector of the time reversal operator, it is possible to record the whole time reversal operator and compute its eigenvectors decomposition. Thanks to this numerical eigenvector decomposition, a selective focusing on each target can be achieved. Using this technique, known as the DORT method, Chambers recently shown that the spectrum of the time reversal operator can be complex and very informative [9].

Nevertheless, the D.O.R.T method suffers several limitations as it requires the measurement of the NxN inter-element impulse responses and the computation of the eigenvector decomposition is quite time consuming and does not allow real time imaging.

A new real time technique has been recently proposed by G.Montaldo et al [10] for multitarget selective focusing that does not require the experimental acquisition of the time reversal operator. Actually, this technique achieves the operator decomposition simply by using a particular sequence of iterative wave illuminations instead of computational power. The general idea of this new approach is first to use the time reversal iterative process in order to estimate the signals focusing on the brightest target. These signals are then used to derive a cancellation filter allowing canceling target's echoes during the selection of the next brightest spot by iterative time reversal. This process can be extended to following multiple target detection using the cancellation filter that cleans up the targets already detected.

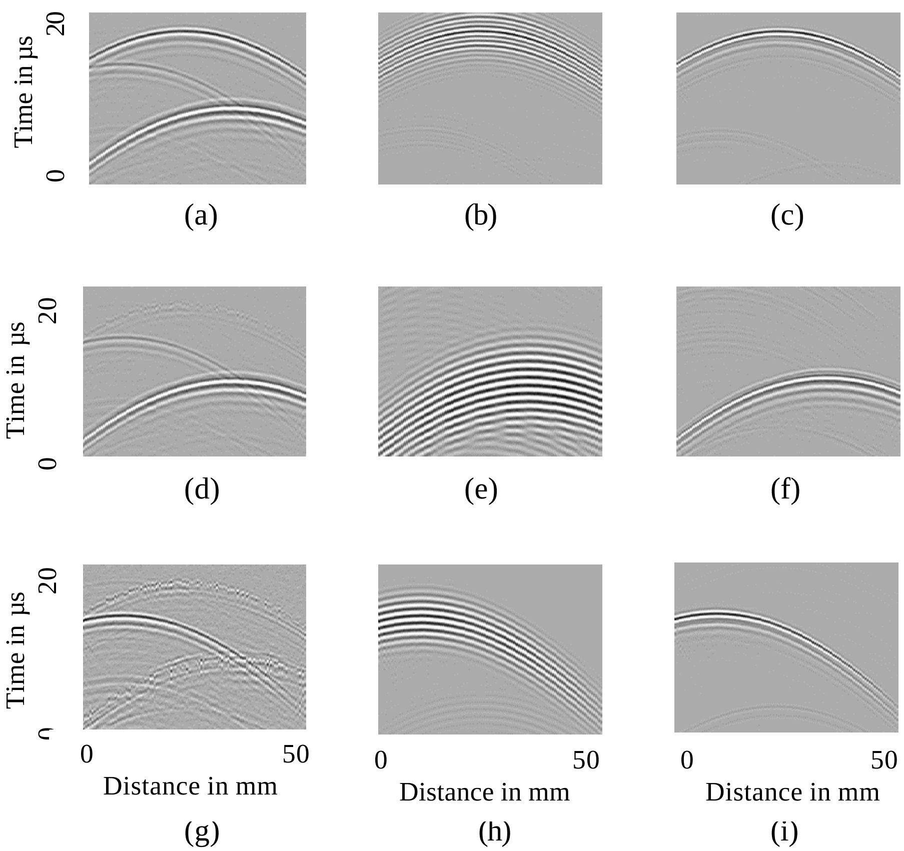

FIGURE 1. The iterative process. a) Echoes from the 3 scatterers after a plane wave emission. b) Detection of the strongest scatterer by iterative time reversal. c) Eigenpulse of the first scatterer. d) Echoes from the two scatterers after filtering the first one. e) Detection of the second scatterer by time reversal and filtering . f) Eigenvector of the second scatterer. g) Signal of the 3rd scatterer after filtering the first and second. h) Detection of the 3rd scatterer by time reversal and filtering. i) Eigenpulse of the 3rd scatterer.

A plane wave is first emitted in this medium. The backscattered signals are composed of three wavefronts of different amplitudes corresponding to each target (Fig. 1a). If these signals are time reversed and reemitted through the medium, the resulting wavefronts focus on each target and the brightest target is more illuminated than the others. Consequently, its contribution in the backscattered echoes is more important. After a few iterations this time-reversal process permits to select the most reflecting scatterer. However, at each iteration the signals are filtered by the limited bandwidth of the transducers and it results in a progressive temporal spreading of the emission signals. In Fig. 1b we can see the received signal after 8 iterations of the time-reversal process, the strongest scatterer was selected but the bandwidth was clearly reduced. The second step of the process allows for overcoming this problem.

The bandwidth narrowing suffered during the time reversal process is a real drawback in most applications. An easy solution consists of reconstructing wideband wavefront at each iteration by detecting the arrival time and amplitude law of the signals received on each transducer. This arrival time and amplitude law is then used to reemit a wideband pulsed signal identical on each transducer with the corresponding amplitudes and time delays on each transducer. It allows avoiding the bandwidth spreading of the signals during the iterative process. The arrival time and amplitude can be measured by using a simple maximum detection technique for each transducer (Fig. 2). Such a "pulsed" wavefront construction before each time reversal emission allows to correct the temporal spreading of the signals during the iterative process (Fig. 2c and 1c).In general, the use of a simple algorithm for the "pulsed wavefront" construction (for example a maximum detection) can induce some errors in the arrival time estimation. For example, if the signal is composed of several sinusoids as presented in Fig. 2.a, the maximum detection can be limited by a 2? uncertainty (Fig. 2 b). It results in the reemission of an incorrect wavefront at the next illumination. However, most of the energy of this incorrect wavefront is focused on the good location and the maximum detection on the next backscattered echoes becomes easier and more accurate. Thus, a few iterations of the time reversal process combined with the pulse compression allow obtaining a correct pulsed wave front or “eigenpulse” signal. Note that the duration of these combined steps is only limited by the waves travel time and the maximum detection hardware. As an example, for medical applications, the detection of a brightest target located at 50 mm depth in tissues achieved in 8 iterations of these combined steps could last less than a millisecond.

The basic idea for selecting a new scatterer is to filter the signals coming from the detected ones. This filter is built by subtracting the projection of the wave front from the signal each time. If we start with a backscattered signal containing the echoes of the three scatterers (Fig. 1.a), we obtain the filtered signals shown in (Fig. 1d). As one can notice, the echoes of the strongest scatterer have been cancelled. This new set of filtered signals is now used as initial illumination for the iterative time reversal process. The cancellation filter is applied at each step during the iterative time reversal process. Consequently, the second target generates the brightest echoes and is progressively selected by the iteration process (Fig. 1.e). The signals backscattered by the second target are temporally spread and can be “pulse compressed” (Fig. 1.f).

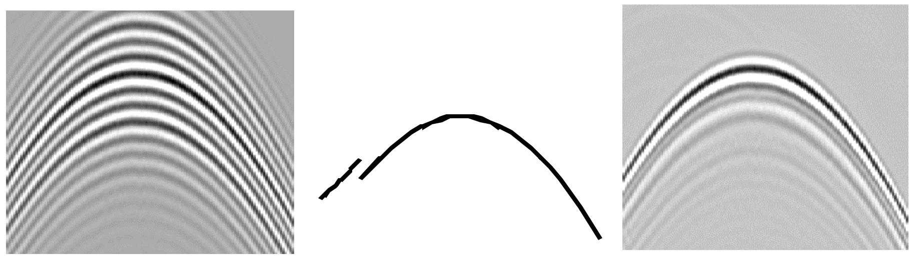

FIGURE 2. a) After the iteration of the time reversal the signal is enlarged. b) Selection of a wavefront only, this wavefront has a defect in the detection. c) After emitting this wavefront, we obtain a narrow pulse, in this narrow pulse thre are not defects in the identification of the wavefront.

Finally, the cancellation filter allows cancelling the first and second target and selecting the third target by iterating the time reversal process. Figures 1.g, 1.h and 1.i, describe the final eigenvector decomposition that was found for the third and weakest target.

As one can notice, the complete process does not require any fastidious calculation. The combination of a simple maximum detection with the iterative time reversal process was found sufficient in order to select multiple targets. The cancellation filter corresponds also to a simple signal subtraction. The main advantage is the simplicity of the procedures that can be implemented in hardware for real time selective focusing. As an example in medical imaging, the detection of 3 reflectors located at 50 mm depth in tissues could last less than 10 milliseconds!

This technique is also robust in speckle noise as it can be seen, for example, on a biological phantom containing nine wires embedded in a random distribution of unresolved scatterers. Fig. 3a shows the beamformed pulse-echo image of the phantom when it is illuminated with a plane wave. We can see the echoes of some target superimposed to the speckle noise. The iterative method is able to identify easily the 9 echoes as it is shown in Fig. 3b.

Compared to a conventional B scan image (Fig. 3c), our technique is able to perfectly recognize the 9 targets. Using the time delays, the position of each target can be estimated and in Fig. 3d, the positions of the targets are superimposed to the basic image. An interesting application of this technique is the identification of micro calcifications in the breast or other organs. This technique can also be implemented at lower frequency for real time mine detection.

CONCLUSION

Time-reversal shows startling applications in the field of ultrasound. Because ultrasonic time-reversal technology is now easily accessible to modern electronic technology, it is expected that applications in various areas will expand rapidly. Initial applications show promise in medical therapy. We have shown in this paper how passive reflecting targets embedded in the body (kidney stones, breast microcalcifications....) can be used as sources of time reversal waves. The very first, and perhaps most illustrative, application of time reversal concerns, real time tracking and destruction of moving kidney stones during lithotripsy treatment. Iterating the time reversal process leads to also interesting applications as it becomes possible in

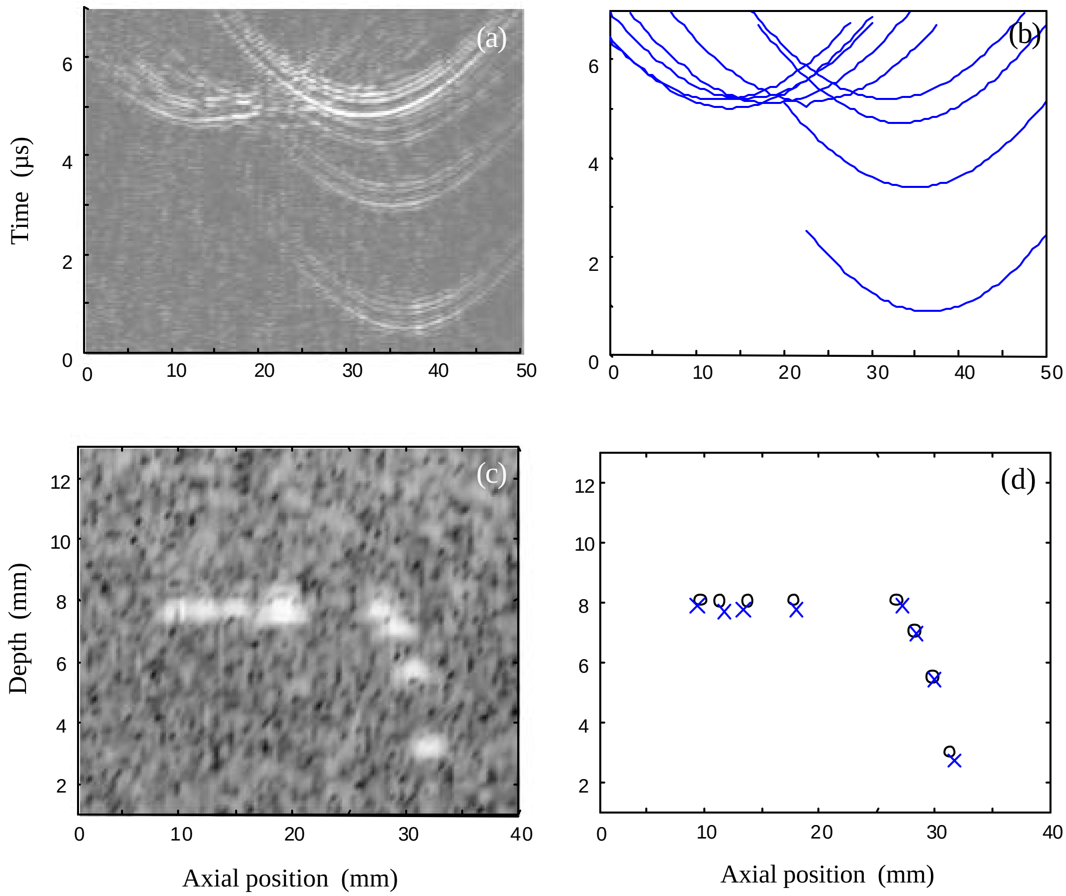

FIGURE 3. Target detection in a biological phantom. a) Signal received after a plane wave illumination, we can see some echoes of the targets with an important speckle noise from the phantom. b) Detection of the echoes of 9 targets. c) B scan image of the phantom. Due to the speckle noise, the smallest targets are difficult to resolve. d) Calculation of the targets positions from the detected echoes. The x are the measured positions and the circles are given by the furnisher of the phantom.

multiple target environments to select and focus in real time on each target of a medium. For this purpose, the ability of iterative time reversal to improve the detection of microcalcifications in the speckle noise of the breast was presented.

Time reversal is also a very powerful correction technique for distortions induced by sound velocity and density heterogeneities. Combined with absorption correction techniques, its potential is currently investigated for the local destruction of malignant brain tumors using trans-skull high intensity focused ultrasound.

Beyond these straightforward applications of time reversal to spatial focusing of waves through aberrating medium, time reversal techniques also allow us to revisit the complete concept of piezoelectric transducer designing. Contrary to conventional transducer technology avoiding unwanted reverberations in piezoelectric elements, time reversal can benefit from strongly reverberating media to create virtual transducers and thus to obtain a very high focusing quality with a small number of transducers. New generation of ultra-compact shock wave lithotripters can be implemented with this approach. The application of this breakthrough concept for 3D medical imaging is also being currently investigated.

All these applications of time reversal were discussed in the field of linear acoustics, but a very interesting point is that time reversal properties remain valid in the field of nonlinear acoustics. We are currently envisioning that time reversal techniques can also be very useful in nonlinear acoustics as it could enhance the image contrast in medical harmonic imaging.

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