Time Reversal of Ultrasonic Fields—Part II: Experimental Results

Francois Wu, Jean-Louis Thomas, and Mathias Fink

Abstract—A time-reversal mirror (TRM) is made of an array of transmit-receive transducers. The incident pressure field is sampled, digitized, stored, time-reversed and then re-emitted. This process can be used to focus, through inhomogeneous media, on a reflective target that may behave as an acoustic source after being insonified. A 64-channel prototype has been built and TRM experiments demonstrating the TRM performance are described. Present first is focusing experiments conducted on point targets through different aberrating media. The major result shows that the time-reversal focusing technique compensates for all the distortions whatever the TRM-aberrator distance. When the medium contains several targets, we show that the time-reversal process can be iterated in order to focus on the most reflective one. The last part of the paper deals with lithotripsy applications. Kidney stones are spatially extended targets and TRM experiments have been conducted on several kidney stones located behind inhomogeneous media. They show that the iterative TRM process is able to select one of the kidney stones and to focus on a small portion of it.

I. INTRODUCTION

INTEREST has developed in using large ultrasonic transducer arrays in applications requiring a very narrow beam such as high-resolution imaging, high-power insonification, target counting and high-accuracy tracking. Such problems occur in medical applications (imaging, lithotripsy and hyperthermia) as well as in non-destructive testing and underwater acoustics. Very narrow beams can be obtained by ordinary beamforming techniques. The transmitted and the received signals pass through a bank of delay lines. The delays are adjusted to form a focused beam and to scan it across the region of interest. Depending on the array geometry, cylindrical or spherical delay laws can be implemented.

However, large arrays may suffer from strong geometrical distortions that should be corrected. Besides, the focusing of ultrasonic waves becomes a difficult operation as soon as the medium of propagation contains local heterogeneities (spatial variations of the compressibility and/or the density). In such conditions, the acoustic beam can be distorted and redirected, so that optimal focusing cannot be achieved. Compensation for these two kinds of distortions must be self-adaptive because the designer has no a priori knowledge on them. Self-adaptive techniques generally require the presence of a point-like target. The need for a point source for system and medium calibration limits the use of self-adaptive method especially in uncontrolled environments.

If a point source or a point target is available in the region of interest, the most general approach consists in the evaluation of a compensating time-delay characteristic that is superposed to the spherical one [1], [2]. The echoes from the target drive the array. The received signals are cross-correlated and the proper time delays are determined by the time shift corresponding to the maximum of the cross-correlation between signals from neighboring transducer elements. Although cross-correlation techniques are very attractive, however they suffer from two important limitations. One is related to the nature of the target available in the medium. The other limitation results from the nature and the location of the inhomogeneous medium.

The first limitation of the cross-correlation technique is that a beacon signal cannot be expected everywhere in the medium. Different authors have shown that a point-like target can be replaced by a random distribution of scatterers as the ones contained in biological tissues [1]–[5]. The cross-correlation technique is then applicable because of the spatially incoherent nature of the backscattered field. Spatially incoherent sources are obtained if the size and the mean distance between each individual scatterer is typically much smaller than the resolution cell of the focusing array. In this case, neighboring transducers will sense echographic signals that are highly correlated [6].

However, when the region of interest contains one or several specular reflectors of extended dimension, the cross-correlation technique is not applicable because of the spatially coherent nature of the reflected field. A kidney stone or a bone have a size greater than the wavelength and the individual echoes originating from these reflectors can be very different from one transducer to the other and then difficult to cross-correlate. In the case of a medium containing several reflectors, the echo pattern becomes so complicated that the cross-correlation technique cannot converge.

Another limitation of the cross-correlation technique comes from the fact that this method reduces to the determination of a time-delay across the array. Time-delay focusing is a valid technique in homogeneous media. It can also correct for unknown geometrical distortion of the array and for the effect of a thin aberrating layer located close to the array. Indeed, thin random layers as well as time-shift errors due to any geometrical distortion act only as random time-delays, variable from one transducer element to another. However, in many situations, the acoustic inhomogeneities are not only located near the array, but are distributed in the whole volume. A
wave originating from a point source and propagating in such an inhomogeneous medium is not only delayed. Its spatial and temporal shape is also distorted through refraction, diffraction, and multiple scattering. In such case optimal focusing cannot be achieved with only delay-line techniques.

Optimal focusing, valid for any kind of inhomogeneous medium, needs to take into account all the information received on the array from the point source (e.g., time-delay and waveform modifications of the individual signals recorded on each transducer element).

The time-reversal processes represent an original solution to these different problems. Time-reversal mirrors take advantage of the invariance of the wave equation under a time-reversal operation \([7],[8]\). This means that if we want to focus in the transmit mode through any inhomogeneous medium, it is enough to record the distorted wavefield coming from a source (active or passive) located at the desired focal point and to time-reverse this field. The time-reversed wavefield backpropagates through the inhomogeneities and optimally refocuses on the source \([7],[8]\).

A time-reversal mirror consists of a one- or two-dimensional transducer array. Each transducer element is connected to its own electronic circuitry that consists of receiving amplifier, A/D converter, storage memory, and, most importantly, a programmable transmitter able to synthesize time-reversed version of the signal stored in the memory.

To focus on a point target through an inhomogeneous media, the basic scheme requires three steps. In the first step (illumination step), the array illuminates an angular sector that contains the target. The echoes from the target are distorted by the inhomogeneous medium and are recorded by the array in the second step (receiving step). Then in the last step (focusing step), the array retransmits the time-reversed field. When the target is spatially extended and/or when there are several targets in the illuminated beam, the time-reversal process can be iterated \([7]--[9]\). The iterative mode allows selective focusing on the most reflective target and the final transmitted beam converges on a small portion of this target.

This research was first aimed at overcoming lithotripsy limitations. Tracking of kidney and gall bladder stones moving through inhomogeneous tissue is difficult. The stone motion due to breathing can be as large as 2 cm. The iterative time-reversal technique can solve these problems.

In this paper, we first describe the TRM apparatus and TRM experiments with a point-like source (active or passive) through different aberrating media. Then, we increase the complexity of the experiments (multiple targets) and we finally report a set of in vitro experiments on kidney stones observed through aberrating media.

In a first section, we describe the experimental setup made of 64 programmable transmitters and we show a simple example of the transmitter ability to generate the matched-filter characteristic of the acoustoelectric response of any transducer.

In the second section, we present a set of focusing experiments conducted on point sources or point targets. The first experiment shows the ability to compensate focusing for a geometrically distorted array. The second experiment shows the ability to redirect a narrow beam deflected by a silicone prism aberrator. The last set of experiments is conducted with an aberrating layer whose thickness is randomly modulated and that widely defocuses the transmitted beam. The main interest of this experiment is to show that the time-reversal focusing technique compensates for all the distortions whatever the TRM-aberrator distance.

In the third section, we study the time-reversal focusing on a multi target medium made of simple targets (wires in front of a linear array). We show the ability to select the most reflective target in the iterative mode.

The last section deals with in vitro lithotripsy experiments. Different kidney stones have been located behind an aberrating medium. We show the ability of TRM to select one stone and to focus the beam on a spot of reduced size.

II. EXPERIMENTAL ARRANGEMENT

A. Electronics

Experimental data on time-reversal mirrors have been obtained with an electronic prototype made of 64 programmable transmitters. Each programmable transmitter is driven by a 4 k byte buffer memory through a D/A converter operating at 25 MHz sampling rate, allowing storage of a 160-μs interval. In the transmit mode, the 64 transmitters work simultaneously and are connected to a 64-element transducer array.

We developed our own electronic circuitry that delivers a 175 V peak-to-peak maximum voltage to a 50-Ω transducer impedance. However, the dynamic range of the transmitter is 6 bits between 0 and 175 V.

In the receive mode, a single A/D Lecroy converter is used through a multiplexer so that recording a complete set of A-lines requires 64 consecutive emissions. This limitation does not allow full real time operation. Recorded data are digitized at a sampling rate up to 100 MHz with an 8-bit dynamic range. A sampling rate 8 to 10 times higher than the central transducer frequency is needed to obtain a good focusing quality. The 64 recorded signals are transferred to a Compaq 386 computer that controls the time-reversal process and the matching of the dynamic range between the receive (8 bits) and the transmit mode (6 bits). When all the 64 signals are stored in the computer memory, they are time-reversed and then transferred to the 64 buffer memories. The 64 time-reversed waveforms are then simultaneously fired from the transducer array.

B. Transmitter Performance: The Transducer Acoustoelectric Matched-Filter

In order to evaluate the programmable transmitter performance, we conducted a simple experiment on a single channel. One of the transmitters was connected to a disk plane transducer illuminating, at normal incidence, a stainless steel plane mirror. The transducer and the mirror were immersed in a water tank. In the first step, the transducer (3.5-MHz central frequency) was driven by a very short electrical pulse (40-ns duration). The echographic signal \(h(t)\) was recorded and stored (Fig. 1(a)). The waveform is the transducer acoustoelectric response in the transmit-receive mode. Note that in this 1-D experiment, the diffraction effect is reduced to a single
propagative delay. The signal $h(t)$ is time-reversed after a delay $T$ and then re-emitted by the transducer. The new pulse-echo signal obtained from the steel mirror is then recorded and shown on Fig. 1(b). Taking into account the linearity of all the processes, this last signal results from the convolution product of $h(t)$ with $h(T-t)$. Such a signal is necessarily symmetrical, that is confirmed by Fig. 1(b). The use of $h(T-t)$ as the driving pulse realizes the acoustoelectric matched filter, giving the maximum pulse echo signal at time $T$, for a specified transmitted energy. Such result explains the very good sensitivity of all the transducers working in time-reversal mode.

C. The Transducer Arrays

Time-reversal experiments have been performed with different kinds of transducer arrays. The basic experiments presented in Sections I–III use two one-dimensional (1-D) mirrors working at 3.5 MHz and are referred to as TRM1 and TRM2. The lithotripsy experiments presented in Section IV have been conducted with a two-dimensional (2-D) prefocused array working at 1 MHz and is referred to as TRM3.

Each element of TRM1, TRM2, and TRM3 was electrically matched to a 50-Ω load with a L-C matching network.

TRM1 has been specially designed for TRM experiments. It is a prefocused cylindrical time-reversal mirror made of a 64 element linear array. Each of the transducer elements is rectangular, 0.5 mm wide, and 10 mm high. The array pitch is 0.6 mm and the elements set out on a cylindrical backing of 80 mm radius of curvature (Fig. 2). The total aperture of TRM1 is thus equal to 40 mm with an 80 mm natural focal length. This array suffers from geometrical distortions. Two elements are out of line and record pulse-echo signals shifted of more than 0.8 ms compared with the adjacent elements. TRM1 has been used to demonstrate compensation of geometrical distortion and redirection of a narrow beam.

TRM2 is a 1-D plane time-reversal mirror made of a plane linear array used for medical imaging applications. It is made of 128 transducers 10 mm high and 0.6 mm wide. The array pitch is 0.75 mm and the working frequency is 3.5 MHz. We use only the 64 consecutive elements located in the middle of the array corresponding to a 48-mm maximum aperture. TRM2 has been used for demonstrating automatic self-focusing through aberrators and target selection in multi-target experiments. In lithotripsy experiments, we used a 2-D prefocused mirror working at 1 MHz. TRM3 is a part of a 2-D curved array. Each transducer element is a plane disk of 6-mm diameter and the 64 elements are arranged on a
spherical cup of 120 mm radius of curvature. The transducers in an hexagonal mesh and distributed according in five-row structure of respectively 12, 13, 14, 13, and 12 elements (Fig. 10). The maximum aperture of the array is 120 mm along the rows, with an average element center-to-center spacing of 8 mm. In the orthogonal direction, the array is 40 mm.

III. FOCUSING ON POINT SOURCES OR POINT TARGETS

All the TRM experiments are performed in a water tank. The focusing experiments require active point sources or passive point targets. For this purpose, we use Dapco needle point hydrophones. They can be used as active transmitting point sources. The hydrophone is then driven by a pulse emitter (Panametrics 5052PR) and the directivity pattern of the transmitted pressure waveform is practically omnidirectional. They can also be used as passive reflectors to simulate point targets. In this case, the needle axis is parallel to the array axis. Lastly, to monitor the time-reversal focused beam, the same hydrophone is used in receive mode. The hydrophone is moved by stepper motors and scans the region of interest.

A. Focusing Compensation for Geometrically Distorted Array

The first experiment has been conducted with TRM1, which is the geometrically distorted 1-D array. The experiment is performed using a Dapco needle point hydrophone as an active transmitting point source. The cylindrical array and the point source are immersed in a water tank. TRM1 is geometrically prefocused at a depth \( z = 80 \text{ mm} \). The hydrophone location \( r_0 \) was far from the geometrical focus of TRM1. It was located at a depth \( z_0 = 40 \text{ mm} \) from the surface of the mirror and 10 mm away from the array axis corresponding to the coordinates \( r_0 = (40 \text{ mm}, 10 \text{ mm}) \). See Fig. 2. The pressure wave transmitted by the hydrophone was recorded on the 64 elements of TRM1. Thirty-two of the resulting signals are shown in Fig. 3(a). They line up according to an oblique cylindrical law corresponding to the location of the out-of-focus source. We observe that two transducers of the array are out of line. They deliver pressure signals before the neighboring transducers.

The time-reversal experiment was conducted in two steps. In the first step, the individual signal recorded by each transducer was time-reversed and transmitted alone. The hydrophone was used in the receive mode to monitor the pressure field at the initial location of the source. Fig. 3(b) shows the individual signals measured by the hydrophone corresponding to the individual transmission of each transducer element of TRM1. All the individual time-reversed waves reach their maximum at the same time \( T \) at the source location \( r_0 \) as predicted by the TRM matched-filter theory developed in the companion paper [8]. In the time-reversal process, the earlier signals corresponding to the shorter transit times are retransmitted later, such that all the individual signals reach their maximum at the same time. The time-reversal process cancels the defects of the array.

In the second step, all the elements simultaneously retransmit the time-reversed field of Fig. 3(a), therefore resulting in a constructive interference of all the individual waves of Fig. 3(b) at time \( T \) at the source location \( r_0 \). The TRM focusing pattern was obtained by scanning the plane \( z = 40 \text{ mm} \) with the hydrophone working in the receive mode. The maximum of the pressure field was computed for each hydrophone position. Fig. 4 represents the directivity pattern. It reaches a maximum at the initial source position \( r_0 \) (40 mm, 10 mm).
This experiment shows that TRM focusing is self adaptive and accomplished automatic compensation for geometrical distortions of the array.

B. Focusing through a Deflective Prism

This experiment was done in two steps with TRM1 and a silicone aberrating layer. The aberrating layer is shaped like a prism with a weak parabolic curvature and has a variable thickness in the lateral direction, with a maximum thickness about 15 mm, and a uniform thickness in elevation. The top angle of the prism is about 4 degrees and the ultrasonic velocity in silicone is about 1000 m/s.

The first step shows the silicone layer effect on the cylindrical focusing of TRM1. The layer is located at \( z = 40 \) mm and the TRM1 focal plane \( (z = 80 \text{ mm}) \) is scanned by the hydrophone. The maximum of the pressure field is plotted on Fig. 5(a), when all TRM1 elements are driven together with an identical short pulse. The acoustic beam is refracted by the prism and it focuses 4 mm off the transducer axis.

The second step of the experiment illustrates the time-reversal focusing process. The hydrophone was used as a point-like reflector located at the natural focus \( RF (80 \text{ mm}, 0 \text{ mm}) \) of TRM1. TRM1 illuminated an angular sector containing the target. The echoes from the hydrophone target were distorted by the silicone layer and recorded on the array. The corresponding signals were time-reversed and reemitted. The time-reversed waves propagate through the aberrator and the time-reversed pressure field was measured by scanning the focal plane with the same hydrophone now working in the receive mode (Fig. 5(b)). We note that refocusing occurs exactly at the hydrophone initial position RF. This experiment supports the TRM distortion compensation procedure.

C. Focusing through a Random AbERRating Layer (The Effect of the TRM-AbERRator Distance)

In this set of experiments, we used the plane 1-D mirror TRM2. As in the previous experiment, the TRM target was the needle hydrophone used as a passive reflector. The target was observed through a strongly aberrating medium. The experiment was carried out for different TRM-aberrator distances. The aberrating medium was made of a rubber layer with a randomly modulated thickness. The ultrasonic velocity in the rubber was about 1200 m/s. The layer was shaped with a random profile in the lateral direction and a uniform thickness in elevation. The random profile induced a random shift in the layer transit time, the standard deviation of this shift is about 0.15 \( \mu \text{s} \) compared to the acoustic period 0.3 \( \mu \text{s} \) of TRM2. In addition, the coherence length \( L \) of the random delay at 3.5 MHz is about 12 mm. This corresponds to the mean lateral distance along which the delays change of no more than eight times the acoustic period [10].

The set of experiments was again done in two steps. The first step investigated the distortions introduced by the layer on cylindrical beamforming experiments. Cylindrical beamforming delays were computed in order to focus through homogeneous water at 90 mm from the surface of the array and along the array center line. The 64 elements transmitted an identical pulse through the calculated bank of delay lines and a needle point hydrophone scanned the focal plane \( (z = 90 \text{ mm}) \) for different positions of the aberrating layer. Figs. 6(a)–(d) show the directivity pattern measured in the focal plane (maximum of the pressure field at \( z = 90 \text{ mm} \)) when the aberrator is located at different depths from the linear array. These figures correspond to an array–aberrator distance \( d \) of respectively 0 mm (Fig 6(a)), 27 mm (Fig 6(b)), 47 mm (Fig 6(c)) and 67 mm (Fig 6(d)). The appearance of these figures clearly shows that the maximum defocusing effect is observed for \( d = 0 \text{ mm} \), which corresponds to the aberrator against the array. The beam is widely spread. The -6-dB lateral resolution is about 6 mm and the side lobe level is very high. The -6-dB lateral resolution corresponds to the focusing of an apparent transmitting aperture smaller than the 48-mm-long TRM2 aperture. This result is consistent with theoretical predictions about defocusing due to propagation through random phase plate aberrator [10], [11]. In homogeneous medium, the lateral resolution is
Fig. 6. TRM2 Directivity patterns measured in the plane $z = 90$ mm. TRM2 is a plane transducer array and a random aberrating layer is located between the array and the scanned plane. Figs. 6(a)–(c) and (d) show the directivity patterns measured with a cylindrical beamforming technique corresponding to an array-aberrator distance $d$ of respectively (a) 0 mm, (b) 27 mm, (c) 47 mm, and (d) 67 mm. (e)–(h) The directivity patterns for the same array-aberrator distances with the TRM focusing technique.

The second step of the experiment illustrates the time-reversal focusing process. The hydrophone was used as a point-like reflector located at a depth $z = 90$ mm. For each TRM-aberrator distance, the point reflector was illuminated through the aberrating layer by the incident beams corresponding to the pressure fields of Figs. 6(a)–(d). The echoes from the hydrophone were distorted by the rubber layer and were recorded on the array (See, for example, Fig. 7(a) for $d = 0$ mm and Fig. 7(b) for $d = 27$ mm.) The corresponding

area of the aberrator. Indeed, for a random profile located at a distance $d$ from a probe of focal length $f$, theoretical predictions show that for values of $d$ not too close to $f$, the equivalent aperture of the probe is practically equal to the aberrator coherence length multiplied by $f/(f - d)$ [10], [11].

The second step of the experiment demonstrates the time-reversal focusing process. The hydrophone was used as a point-like reflector located at a depth $z = 90$ mm. For each TRM-aberrator distance, the point reflector was illuminated through the aberrating layer by the incident beams corresponding to the pressure fields of Figs. 6(a)–(d). The echoes from the hydrophone were distorted by the rubber layer and were recorded on the array (See, for example, Fig. 7(a) for $d = 0$ mm and Fig. 7(b) for $d = 27$ mm.) The corresponding

area of the aberrator. Indeed, for a random profile located at a distance $d$ from a probe of focal length $f$, theoretical predictions show that for values of $d$ not too close to $f$, the equivalent aperture of the probe is practically equal to the aberrator coherence length multiplied by $f/(f - d)$ [10], [11].

The second step of the experiment demonstrates the time-reversal focusing process. The hydrophone was used as a point-like reflector located at a depth $z = 90$ mm. For each TRM-aberrator distance, the point reflector was illuminated through the aberrating layer by the incident beams corresponding to the pressure fields of Figs. 6(a)–(d). The echoes from the hydrophone were distorted by the rubber layer and were recorded on the array (See, for example, Fig. 7(a) for $d = 0$ mm and Fig. 7(b) for $d = 27$ mm.) The corresponding

area of the aberrator. Indeed, for a random profile located at a distance $d$ from a probe of focal length $f$, theoretical predictions show that for values of $d$ not too close to $f$, the equivalent aperture of the probe is practically equal to the aberrator coherence length multiplied by $f/(f - d)$ [10], [11].

The second step of the experiment demonstrates the time-reversal focusing process. The hydrophone was used as a point-like reflector located at a depth $z = 90$ mm. For each TRM-aberrator distance, the point reflector was illuminated through the aberrating layer by the incident beams corresponding to the pressure fields of Figs. 6(a)–(d). The echoes from the hydrophone were distorted by the rubber layer and were recorded on the array (See, for example, Fig. 7(a) for $d = 0$ mm and Fig. 7(b) for $d = 27$ mm.) The corresponding

area of the aberrator. Indeed, for a random profile located at a distance $d$ from a probe of focal length $f$, theoretical predictions show that for values of $d$ not too close to $f$, the equivalent aperture of the probe is practically equal to the aberrator coherence length multiplied by $f/(f - d)$ [10], [11].

The second step of the experiment demonstrates the time-reversal focusing process. The hydrophone was used as a point-like reflector located at a depth $z = 90$ mm. For each TRM-aberrator distance, the point reflector was illuminated through the aberrating layer by the incident beams corresponding to the pressure fields of Figs. 6(a)–(d). The echoes from the hydrophone were distorted by the rubber layer and were recorded on the array (See, for example, Fig. 7(a) for $d = 0$ mm and Fig. 7(b) for $d = 27$ mm.) The corresponding

area of the aberrator. Indeed, for a random profile located at a distance $d$ from a probe of focal length $f$, theoretical predictions show that for values of $d$ not too close to $f$, the equivalent aperture of the probe is practically equal to the aberrator coherence length multiplied by $f/(f - d)$ [10], [11].
signals are time-reversed and re-emitted. The time-reversed waves propagated through the aberrator and the time-reversed pressure field was measured by scanning the focal plane with the same hydrophone in the receive mode. Figs. 6(e–h) show the resulting focal beams for $d = 0, 27, 47,$ and $67$ mm. The four directivity patterns are similar and correspond to a $-6$-dB lateral resolution about $1.5$ mm. These results demonstrate the ability of time-reversal focusing to compensate for distortion induced by aberrators whatever the probe–aberrator distance.

In the last part of this section, we wish to discuss a very fundamental point about focusing processes through inhomogeneous media. Focusing with TRM seems to be a complicated technique because a different waveform must be transmitted from each transducer element. In the time-delay technique, this reduces to transmitting the same pulse within a time-delay from each element. However, time-delay focusing is a valid technique to correct for the effect of an aberrating layer located close to the array. Indeed, a thin random layer only delays the signal. A spherical pulse wave originating from a point source is thus delayed by the propagation through the aberrator while the pulse shape is unchanged. This is clearly shown on Fig. 7(a), which corresponds to the hydrophone echoes propagating through the aberrator and recorded when the array–aberrator distance $d = 0$ mm. In this case, transmitting the time-reversed of Fig. 7(a) or transmitting an identical pulse through matched delay-lines gives the same focusing results.

However, when the array–aberrator distance increases, the recorded pressure signals originating from a point source are not only delayed, but their shapes are no longer similar. Fig. 7(b) shows the signals recorded by TRM2 from the hydrophone when $d = 27$ mm. The strong distortions of the recorded signals and the complicated shape of this pattern result from the propagation of the pressure field from the output plane of the layer to the array recording plane ($d = 27$ mm). Although the pressure signals are identical within a time delay on the output layer plane, the interference between all the Huygens’s wavelets originating from this plane results in a complicated pattern that has a different shape. In this case, delay-line focusing techniques become ineffective and time-reversal focusing is the only valid technique to refocus.

IV. TRM Iterative Mode in Multitarget Media

In this section, we study TRM focusing on a multitarget medium and we demonstrate the ability of the iterative mode to select the most reflective target. The experiments have been performed with TRM2 (a 1-D plane mirror). The medium is made of two different wires located at a depth $z = 110$ mm.
Selective focusing in the case of two wires. The time-reversal process is iterated. (a), (c), (e), and (g) show the echographic signals recorded from the two wires after the first illumination (a) and the first (c), second (e), and third (g) iteration of the time-reversal process. (b), (d), (f), and (h) represent the pressure diagrams observed in the wire plane after the first time-reversal process (b) and its iterations.

In the first step, TRM2 illuminated an angular sector containing the two wires. The illuminated beam was transmitted by a single transducer element located at the center of the array. The directivity pattern of a single element is wide. However, the pressure level transmitted by a single element is

from the array. The two wires are parallel to the long axis of each array element (Fig. 8) and they are respectively located on both sides of the array axis. A 1.5-mm-diameter copper wire is located at +7 mm away from the array axis and a 0.7-mm brass wire is located at -13 mm from the axis.
usually weak. In our TRM experiments, we increased the transmitted peak pressure with the programmable transmitters. The transducer element was not driven by a single pulse, but by the electrical input signal matched to its acoustoelectric response. To obtain the matched waveform, we calibrated the emitting element as in Section I-B. The sensitivity improvement of this approach is about 10 dB. After the first illumination, the echoes from the two targets were recorded. Fig. 9(a) shows the recorded data corresponding to two individual wave fronts pointing at the two wires. The recorded signals were then time-reversed and retransmitted. The time-reversed waves propagated and the new directivity pattern was measured by scanning the plane \( z = 110 \text{ mm} \) with the hydrophone. Fig. 9(b) represents the directivity pattern that clearly shows two maxima corresponding to the two target locations. The pressure field reaches a higher value at the location of the copper wire whose scattering cross section is larger than the one of the brass wire. The process was iterated: the new echoes from the wires were recorded, time-reversed and retransmitted, etc. As the process was iterated, the brass wire that reflects less energy received a weaker time-reversed wave. This is clearly shown on Figs. (b), (d), and (h), which correspond to the directivity pattern of the first, second, and third iterations. The brass wire is no longer illuminated after the last illumination. Figs. 9(c), (e), and (g) represent the reflected wavefronts recorded by the array after the first, second, and third iterations. At the end of the iteration process (Fig. 9(g)), only the echoes from the most reflective target remain.

Two particular points may be emphasized:

1) Figs. 9(a), (c), (e), and (g) show that the echo duration becomes longer after each iteration. This is due to the multiple convolutions of the pressure signals by the acoustoelectric impulse response of the transducer elements.

2) The echo pattern shown on Fig. 9(a) is more complex than the simple description made previously. In fact, the two wave fronts are followed by weaker replica. These replica correspond to the acoustic resonance of the two wires. The wires cannot be assumed to point-like targets. They behave as extended sources. When the process is iterated, the target resonances can intensify and Fig. 9(g) shows two replicas appearing symmetrically before and after the principal wave front from the copper wire. The wire diameter can be estimated from the measurement of the time shift between the replica and the principal wave.

These experiments demonstrate the ability of TRM iterative mode to select the most reflective target in a multi target medium. This may be viewed as a learning process that selects among several wave fronts the one coming from the most important reflector. However, the process is complicated by target resonances.

V. LITHOTRIPSY EXPERIMENTS

The last section of this paper is devoted to lithotripsy experiments. The experiments were performed with the prefocused 2-D mirror TRM3 immersed in a water tank (see Fig. 10).
the kidney stone was irregular. Its largest dimension was about 10 mm. The kidney stone was located between 10 mm and 20 mm away from the TRM3 central axis. In the first step, TRM3 illuminated an angular sector containing the kidney stone. The illuminating beam was transmitted by a single transducer element located at the center of the array. After the first illumination, the echoes from the stone were recorded. Fig. 12(a) presents the recorded data. We notice that the signals correspond to the five transducer rows used in TRM3. They line up along five wave front sections. Fig. 12(a) shows clearly the kidney stone resonances. Depending on the transducer element, one or two replicas of the primary wave front can be observed. The kidney stone was not a symmetrical resonator as the wire used in Section III, and the resonance pattern is quite complicated.

In the second step of the experiment, the recorded signals shown in Fig. 12(a) are time-reversed and retransmitted. The time-reversed waves propagate and the pressure pattern is measured in the kidney stone plane with the hydrophone (the kidney stone frame has been removed). Fig. 11(a) shows the directivity pattern along an axis parallel to the transducer rows and passing through TRM3 central axis. The diagram is plotted between 10 mm and 20 mm off axis corresponding to the previous stone location. It can be noticed that this diagram does not completely vanish on the stone boundaries. This is explained by the fact that the stone is an asymmetrical target and that TRM3 is only a part of a full 2-D mirror (14 transducers along one direction and five along the orthogonal dimension). Some information about the stone shape is lost and the time-reversal process is not completely effective. The stone has several sides acting as specular reflectors oriented only in some particular directions, and some part of the reflected beams is not recorded by the limited aperture of TRM3. The stone reconstruction (i.e., the real acoustic image) requires the interference of all the time-reversed beams and a null pressure field outside of the stone location also requires a complete destructive interference.
To overcome this difficulty, the time-reversal process can be iterated. After the first time-reversed transmission, the new echoes from the stone can be recorded, time-reversed and retransmitted, etc. Figs. 11(b) and (c) represent the new pressure pattern after the first and the second iterations, while Figs. 12(b) and (c) represent the echoes from the stone after the first and the second iterations. Figs. 11(b) and (c) show that after the first iteration the time-reversal process selects a small spot on the extended target and focuses on it. In the second iteration, the TRM transmits a relatively narrow beam that intercepts the kidney stone. The -6-dB beamwidth is equal to 4.2 mm whereas the kidney stone width is at least 10 mm.

We have conducted TRM experiments on many kidney stones and we have observed the same converging process in all the cases. After one or two iterations, the TRM selects a small portion of the extended target and the resulting beam focuses on a spot whose dimension is of the order of the diffraction point spread function.

A possible explanation can be given if we generalize the multitarget experiments. Each side of the stone can be considered as one target. The iterative process selects the stone side that reflects the greatest energy. However, the process is complicated by the resonances that take into account the elasticity and whole geometry of the stone. A more rigorous explanation has yet to be found. Whatever the explanation, the experimental result is attractive since it permits automatic selection of a small spot on an extended target.

B. Kidney Stone Selection through Aberrating Media

In our last experiments, we increased the complexity to simulate real situations. The experimental geometry was seriously complicated by the introduction of two kidney stones of similar dimensions behind a strong aberrator (Fig. 13).

The aberrating medium was again made of a thick silicone layer whose thickness is randomly modulated with a maximum thickness of 15 mm and a standard deviation of about 3 mm. The coherence length of the aberrator at 1 MHz is about 15 mm. The aberrator front side was located at a depth \( z = 60 \) mm from the array surface. The two kidney stones were located at a depth \( z = 110 \) mm. The smaller kidney stone was located between +3 mm and +11 mm from the axis and the largest one between -5 mm and -15 mm (Fig. 13).

In the first step, the central element of the array illuminated an angular sector that contains the stones. The echoes from the stones were recorded, time reversed and reemitted. Fig. 14(a) shows the time-reversed pressure pattern in the plane \( z = 110 \) mm. Similarly to the previous section, we observe that the first time-reversed beam does not focus on the two stones. After the first iteration of the time-reversal process, a pressure peak appears clearly at -9 mm from the axis (Fig. 14(b)). It corresponds to a point located on one of the kidney stones (the one located on the negative side of the array axis). A smaller peak also appears at +7 mm, corresponding to the other kidney stone. After two more iterations, the peak corresponding to the second kidney stone (on the positive side) disappears (Figs. 14(c) and (d)). Only one peak remains (at -9 mm from the axis), but with significant secondary lobes. The lobe level can be reduced using larger TRM aperture.

This experiment shows that even in a complicated case, the time-reversal mirror is able to select one stone and to focus on a small portion of it, even through a strongly aberrating medium.

VI. CONCLUSION

Experimental data on time-reversal mirrors have been obtained with a prototype made of 64 programmable transmit-
ters. We have conducted different experiments in order to demonstrate that TRM focusing compensates the distortions introduced by any aberrating medium. We have shown that TRM focusing in the transmit mode is optimal whatever the TRM-aberrator distance.

We also have presented experiments conducted in the iterative mode. It is a very attractive technique that allows selecting of the most reflective target in a multitarget medium. Applications to lithotripsy are described and we have shown that in the case of several kidney stones, the iterative mode allows selection of one of the stones and focusing on a small portion of it even through aberrating media.

All these experiments have been performed with 1-D arrays or part of a 2-D array. A large 2-D array would be excessively costly due to the large number of transmit-receive channels needed. This may be addressed by thinning the array and distributing the elements over the aperture.

ACKNOWLEDGMENT

The authors would like to thank Najet Chackroun, Raoul Mallart and Robert Waag for their help in this work.

REFERENCES


François Wu was born in 1940 in Paris, France. He received the DEA degree in Electronique et Traitement de l'Information in 1966 and the Doctorat es-Sciences degree in Physics in 1982 from Paris XI University, Orsay, France.

From 1967 to 1986 he has worked in the Laboratory of Cristallographie et Physique des Matériaux of Professor P. Périgo in Orsay University. He was first Teaching Assistant of Cristallography and then Maitre de Conférences of Physics at Paris XI University, Orsay. Since 1987 he has been in the Laboratoire Ondes et Acoustique, Paris 7 University, Paris, France, directed by Professor M. Fink. His research activities are in the development of ultrasonic time reversal mirrors for medical applications of focusing in inhomogeneous media and nondestructive control of solid materials.

Jean-Louis Thomas was born in Paris in 1966. He received the DEA degree in electronics from the Paris VI University in 1990. He is currently working toward the thèse 3ème cycle from the Paris VI University, with the Technomed International society, in the Laboratoire Ondes et Acoustiques.

Mathias A. Fink, for a photograph and biography, please see page 566 of this TRANSACTIONS.