THE TIME REVERSAL KALEIDOSCOPE: A NEW CONCEPT OF SMART TRANSDUCERS FOR 3D IMAGING

D. PALACIO, G. MONTALDO, M. TANTER, and M. FINK
Laboratoire Ondes et Acoustique, E.S.P.C.I., C.N.R.S. UMR 7587, Université Paris VII,
Email: delphine.palacio@loa.espci.fr

Introduction

In real time 3D echographic imaging, the acquisition of volumic data set requires the recording of an echo from all the 3D region of interest. Traditionally, two dimensional arrays composed of several thousand of transducers are used to obtain the beam focusing and steering in the volume[1]. However, the design, the connections and the multiplexing required by these 2D arrays are technically complex to realize. Here we present a completely new approach to achieve 3D images with a very small number of transducers using the coupling concepts of time reversal mirrors [2] and chaotic reverberating cavities. The small number of transducers (typically 32) are glued on one surface of the solid cavity, an other face is in contact with the imaged fluid medium (like the body). Thanks to hundred of reverberations inside the cavity, the ultrasonic waves emitted by the transducers are able to focus in any point of the volumic fluid by using time reversal techniques [3]. At each reflection, 'virtual' transducers, images of the real ones by the reflection on the surface of the cavity, are created. As a result, a kaleidoscopic transducer array is obtained from a small number of transducer used in a time reversal mode, and allows equivalent performances than conventional 2D matrices made of thousands of transducers. The coupling of chaotic reverberating cavities with times reversal techniques leads to the concept of a 'smart' transducer. First experimental 3d images obtained with a pioneer prototype will be presented.

Focusing in a 3d volume

The imaging system is a pioneer prototype composed of a 3D Sinai Billiard in duraluminium (50x50x50 mm^3), represented in Figure 1, and 30 transmit single elements.

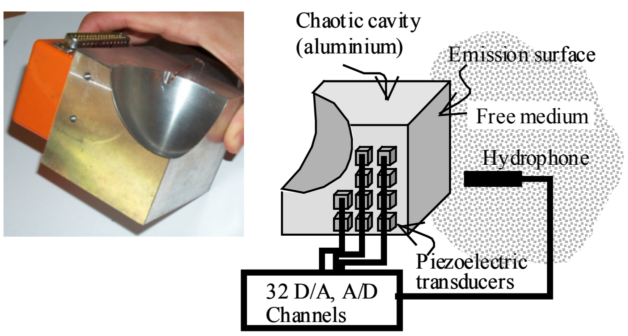

Figure 1. Experimental setup. The kaleidoscope is composed by a chaotic cavity in duraluminium and 31 piezoelectric transducers (0.5 × 0.8 mm) glued on one face. Each transducer is connected to an independent digital-to-analog and analog-to-digital channel. One surface of the kaleidoscope is in contact with the imaged medium.

The transmitters are rectangular piezoelectric ceramics (0.8 × 0.5 mm^2) with a 1.5 MHz central frequency and are glued on one surface of the solid cavity. The bottom face is in contact with the imaged medium, a tank of water simulating the patient's body in usual ultrasonic imaging. Every transducers is connected to a fully programmable multi-channel electronic system (32MHz sampling frequency , 80 V_{pp} / 50 Ω) and is used in a time reversal mode [4].

In order to focus a pulse in any point of the fluid, a time reversal process is implemented. A time reversal experiment is divided in three steps. First, an ultrasonic source placed in the fluid medium, at the chosen focal point sends a short impulsion (typically 2 µs) centered around 1.5 MHz. The acoustic waves propagate inside the medium towards the cavity and penetrate inside the solid medium. Due to the reverberations inside the cavity, waves emitted by the acoustic source are reflected hundred of times and the impulse responses $h_i(t)$, where i is the number of the transducer glued on the cavity, are very long, up to 600 µs (Figure 2).

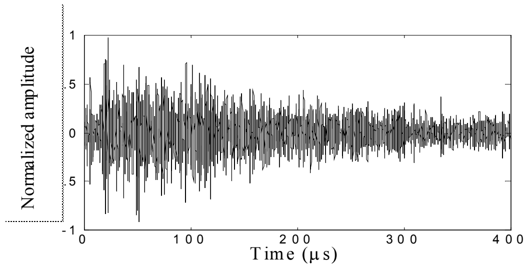

Figure 2. Signal registered by a transducer of the kaleidoscope after sending an impulsion of 2µs from an hydrophone. Due to the multiple reflections on cavity faces, the response is very long (up to 600 µs).

In the second step, a 400 µs temporal window of these impulse responses is selected, recorded as a 1-bit signal [4], time reversed, and retransmitted by the same channel back to the hydrophone. In the last step, the time reversed field is recorded in the source plane by the hydrophone that can move in the two directions. The ultrasound wave has done the way back to the focal point, and the signal recorded at this point is temporally compressed in a short pulse of 2 µs with sidelobes at 38 dB (Figure 3(a)). Ultrasonic waves take benefits of cavity reverberations creating virtual transducers to focus in any point of the fluid by using time reversal techniques. In order to observe the spatial quality of focalization by time reversal, the c-scan (Figure 3(c)) is recorded by the hydrophone. The signal-noise ratio (SN) is about 30 dB for the spatial observation of the focalisation with 30 transmit elements.

This SN is not enough for a focalization in order to build an image. As the amplitude at the focal point is sufficient to generate non linear effects and produce, in particular, harmonics of the incident beam, harmonic detection is used to improve the quality of focalization. After the same time reversal experiment with a pulse inversion that eliminates linear effects, the harmonic signal (centered at 3 MHz) is extracted by a high-pass analogical filter. The temporal compression (Figure 3(b)) of the harmonic signal presents sidelobes at 60 dB, there is a gain of 22 dB compared to the fundamental signal. For the c-scan (Figure 3(d)), the quality of the signal recorded is better since the SN has changed from 30 dB to 50 dB.

As the harmonic sources depend on the square of the incident pressure field amplitude [5], the directivity pattern of the first harmonic is cleaned of spurous signals.

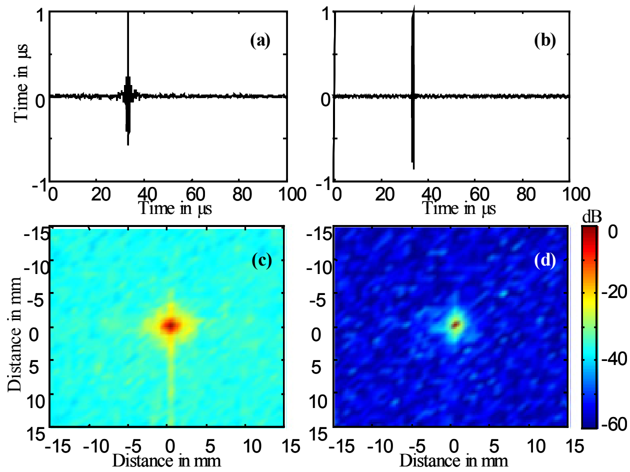

Figure 3. (a), (c) fundamental signal : (a) Signal recorded by the hydrophone at the focal point : temporal recompression. (c) C-scan of the focalization. (b) harmonic signal recorded by the hydrophone at the focal point. (d) C-scan of the harmonic focalization.

Imaging with the cavity

This focusing quality in the transmit mode is good and could provide 3D echographic images with a good contrast.I order to produce an image, the backscattered echoes have to be recorded. The receive mode uses only one receiver because the purpose was to study the feasibility and the capacity to product images of the system. The receive element is an single omnidirectionnal transducer stuck on the front face of the kaleidoscope and centered in the harmonic frequency. The image of the 3D volume is performed with time reversal. The first step of building an image is a calibration. The system has to learn how to focus in every points of the region of interest. For all this points, the time reversed impulse responses are recorded and stored in the computer memory. A data base of impulse responses is obtained. In the second step, the imaged object is introduce in the water tank and for every point, the time reversed impulse responses are sent back. The echo, due to the presence of the object, is recorded by the receiving element. An exemple of a backscattered echo is represented in Figure 4.

The first experimental 3D images obtained with the cavity are presented in Figure 5.

This system is able to produce 3D images with a very small number of emitters and receivers. The surface of objects is easily detected.

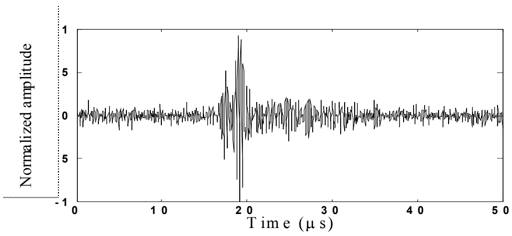

Figure 4. Echo from the object recorded by the receiver.

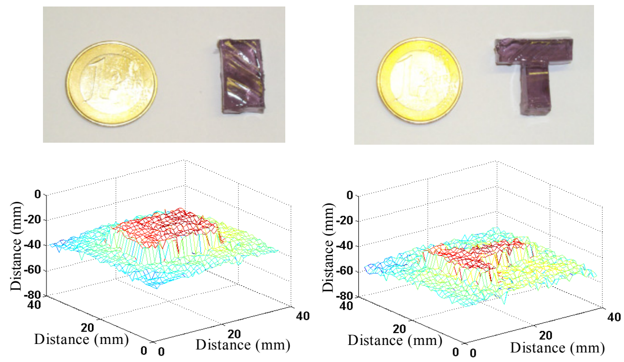

Figure 5. 3D images of a phantom object obtained with the kaleidoscope using 30 emitters and only one omnidirectionnal receiver.

Conclusion

We demonstrated the feasibility of a 3D imaging system using the combined concepts of time reversal mirrors and chaotic reverberating cavities. Harmonic imaging is used to improve quality of focalisation and first images have been presented. In order to improve image quality, the concept of smart transducers can be extended by using more transducers in the receive mode and a prototype combining 64 transmit and 64 receive elements is currently under construction. This technique has a strong potential for pulse echo medical imaging as well as for 3D shear source generation in soft tissues activated by the ultrasonic radiation force. This technique has a strong potential for pulse echo medical imaging as well as for 3D shear source generation in soft tissues activated by the ultrasonic radiation force.

References

[1] E.D. Ligth, R.E. Davidsen, J.O. Fiering, T.A Hruschka and S.W. Smith “Progress in two dimensional arrays for real time volumetric imaging”, Ultrasonic imaging, 20,235-250, 1998.

[2] M. Fink, “Time-reversed acoustics,” Scientific American, pp 67-73, November 1999.

[3] C. Draeger, J.-C. Aime, M. Fink “One-channel time-reversal in chaotic cavities: experimental results”, J. Acoust. Soc. Am. 105 (2),pp 618-625,1999.

[4] G. Montaldo, P. Roux, A. Derode, C. Negreira and M. Fink, “Ultrasonic shock wave generator using 1-bit time-reversal in a dispersive medium : application to lithotripsy”. Appl. Phys. Lett. 80 (5), pp 897-899, 2002.

[5] M. F. Hamilton and D. T. Blackstock, Nonlinear Acoustics, Academic, New York, (1998).