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

Gabriel Montaldo*, Delphine Palacio, Mickael Tanter and Mathias Fink
Laboratoire Ondes et Acoustique, 10, rue Vauquelin, 75005 Paris France

Abstract - The design of two dimensional arrays for real time 3D imaging is a major challenge in medical ultrasound. Several thousand of transducers are typically needed to achieve the beam focusing and steering in a large 3D region of interest. Here we report a completely new approach for producing 3D images with a very small number of transducers using the combined concepts of time reversal mirrors and chaotic reverberating cavities. A small number of transducers glued on the surface of a solid cavity are used in a time reversal mode. If one face of the cavity is in contact with a fluid medium (like the body), ultrasonic waves transmitted by the transducers may take benefit of cavity reverberations to focus in any point of the fluid by using time reversal techniques. Due to the reverberations inside the cavity, waves emitted by each transducer are reflected hundred of times, creating at each reflection ‘virtual ’transducers that can be observed by any observer located in the fluid. The result of such an operation is that a small number of transducers (typically 32) is multiplied by a number greater than hundred to create a kaleidoscopic transducer array presenting equivalent performances than conventional 2D matrices made of thousands of transducers. The time reversal technique allows us to use these ‘virtual ’transducers to focus with a very weak side lobe level on each point of the fluid. First experimental 3D images obtained with a pioneer prototype will be presented. Beyond the scope of 3D medical imaging, this combination of time reversal processing with chaotic reverberating cavities leads to the concept of a ‘smart ’transducer.

I. PRINCIPLES OF 3D IMAGING

Thanks to its moderate cost and non invasive bioeffects, ultrasound imaging has an important role in the diagnostic process of many diseases and physiologic measurement. With 2D conventional ultrasonography of 3D anatomy, the diagnostician is limited to quantify and visualize most diseases because he must integrate many 2D images to reconstruct mentally a 3D volume. Over the past few years, advances in technology that include high speed computing and storage hardware has permitted 3D ultrasound imaging by displaying the volumic region of interest in a single image. To obtain a volume data set, echo must come from all the volume of interest. Two different approaches have been developed to acquire volumic data. The first type of 3D ultrasound system uses a series of 2D images produced by a conventionnal 1D array [1]. The 1D array is moved by the pratician or by a motorized device in the perpendicular direction to the image plan to get a volumetric data acquisition. The scanning requires a position sensor in order to know precisely the position and angulation of each slice. The volumic ultrasound data set and the position data set are necessary to reconstruct the 3D image. The main disadvantages of this method are the sensitivity of the 3D reconstruction to the accuracy of position data and to the artefacts caused by respiratory motion. Both will create distortions in the final image. The second type of 3D ultrasound system uses a 2D array [2]. The number of piezo-electric transducers is extremely high (up to 10000 elements). This approach is the most convenient for the pratician and would produce images of higher quality and higher rate because a 3D focusing of the ultrasound wave is possible. Unfortunately, this technique involves a few technological problems: the high number of elements requires a complex and expensive electronic multiplexing. Here, we present a new and original approach. We try to replace a 2D array by a system of less than one hundred elements. The solution is based on coupling a few number of transducers and a chaotic cavity with one face in contact with the patient body. The reverberations of the ultrasonic wave inside the cavity create at each reflection virtual transducers located on every surfaces of the cavity [3]. The multiple reflexions of the ultrasound waves inside the cavity allow the same quality of focalisation than the one obtained with conventional 2D arrays made of thousands of transducers. The reverberating cavity acts as a kaleidoscope for the small number of transducers used (typically 32) and create a much larger virtual transducer array.

II. FOCUSSING IN A 3D VOLUME

The imaging system is a pioneer prototype composed of a solid chaotic cavity in duraluminium, represented in Figure 1, and 31 transmit elements.

Figure 1. Chaotic reverberating cavity with 31 transmit elements.

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

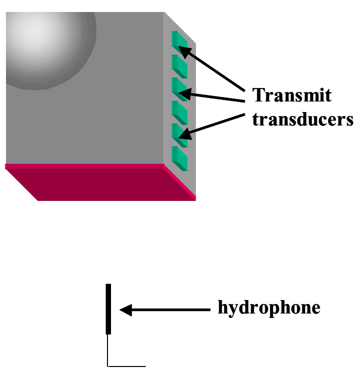

Figure 2. Experimental setup.

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 3).

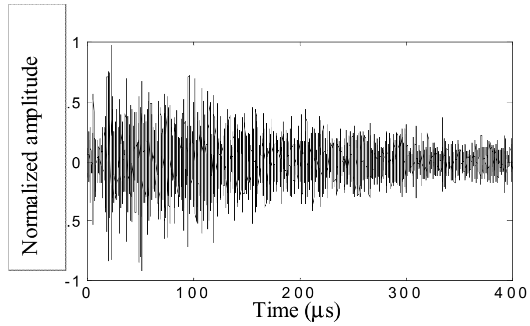

Figure 3. Impulse response recorded by one transducer glued on the cavity.

In the second step, a 400 µs temporal window of these impluse responses is selected, recorded as a 1-bit signal [5], 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 28 dB (Figure 4(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 focalisation by time reversal, the c-scan (Figure 4(b)) are recorded by the hydrophone. The signal-noise ratio (SN) is about 22 dB for the spatial observation of the focalisation with 31 transmit elements.

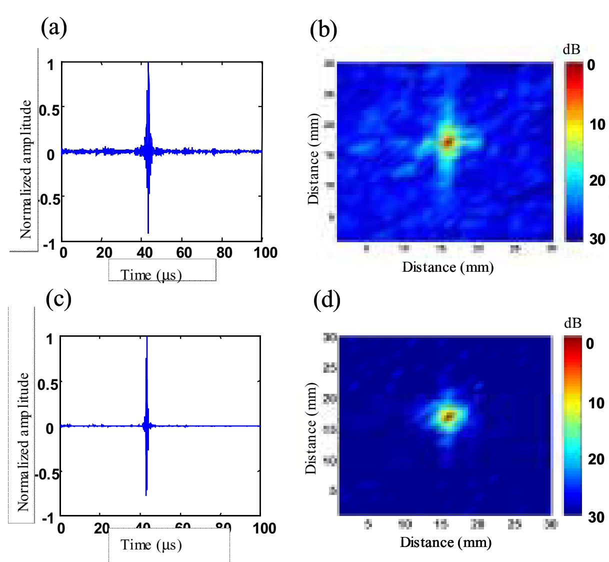

Figure 4. (a), (b) fundamental signal : (a) Signal recorded by the hydrophone at the focal point : temporal recompression. (b) C-scan of the focalisation.

(c) harmonic signal recorded by the hydrophone at the focal point. (d) c-scan of the harmonic focalisation.

This SN is not enough for a focalisation 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 focalisation. 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 hight-pass analogic filter. The temporal compression (Figure 4(c)) of the harmonic signal presents sidelobes at 40 dB, there is a gain of 22 dB compared to the fundamental signal. For the c-scan (Figure 4(d)), the quality of the signal recorded is better than the one of the fundamental since the SN has changed from 22 dB to 31 dB.

The harmonic detection allows to improve the contrast of the focalisation by 1-bit time reversal.

III. IMAGING WITH THE CAVITY

In the previous part, the transmit mode of the imaging system has been presented. The receive mode used only one receiver because the purpose was to study the feasibility and the capacty to product images of the system. The receive element is an hydrophone located in the center of the cavity face in contact with the fluid medium.

The image of the 3D volume is performed with time reversal. The first step of buiding 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 hydrophone located in the centre of the cavity face. An exemple of this sort of echo is represented in Figure 5.

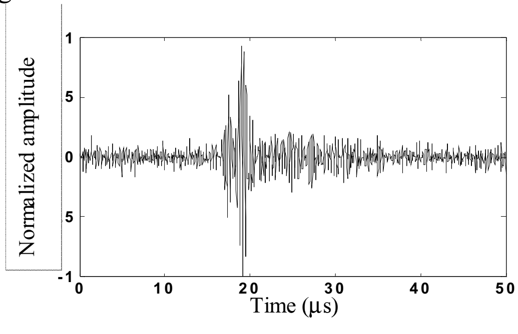

Figure 5. Echo from the object recorded by the receiver.

The first experimental 3D images obtained with the cavity are presented in Figure 6.

(a) (b)

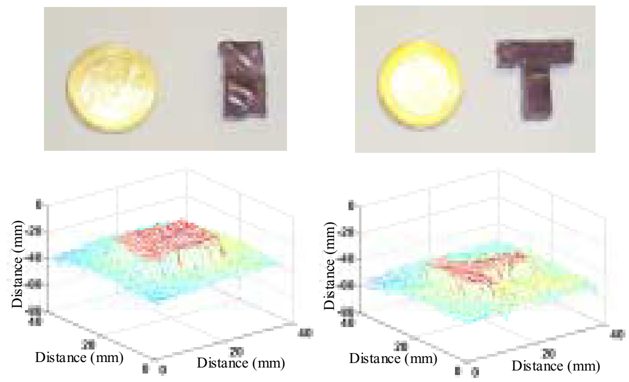

Figure 6. pictures and imaged of two objects obtained with the cavity.

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

IV. 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 make better images, new cavity with a higher number of transmit and receive transducer will be built.

V. REFERENCES

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* email : gabriel.montaldo@loa.espci.fr