Real time beam steering using a one channel time reversal mirror coupled to a solid cavity

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Introduction

Beam steering and beam forming is achieved using a time-reversal process and a unique transducer coupled to a solid cavity[1]. This low cost technique allows one to focus acoustic energy anywhere on a 3-D domain with a spatio-temporal resolution comparable to multiple transducers array. We first record the signal emitted by the transducer and detected by a hydrophone needle at a reference point. The signal received is then time-reversed and remitted using the same transducer. At the reference point one can observe a spatio-temporal recompression. To focus in another point, the source is moved and same process is applied. Finally a set of reference impulse responses is acquired. It allows one to focus ultrasounds anywhere in the 3D domain.

More over, it is shown how the experimental Green's functions at the surface of the cavity can be used to control the emitting ultrasonic field. The signal-to-noise ratio of such a system is explained by a modal theory and leads to define four influencing parameters: the frequency bandwidth, the number of transducers, the geometry of the cavity and the time reversed signal duration. Finally a one channel spatio-temporal Inverse filter is compared to the time reversal efficiency.

Principle of time reversal with a cavity

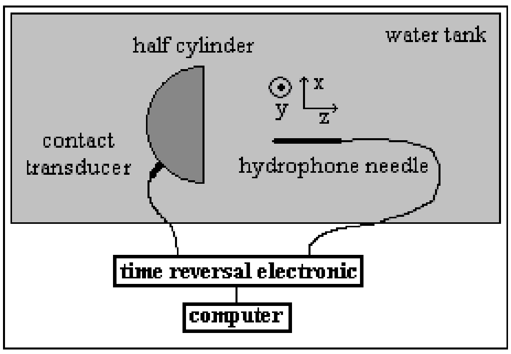

Figure 1: Top view of the experimental setup. The contact transducer is fixed to the duralumin half-cylinder and the hydrophone needle is moved in a 3D domain

Our experimental setup, Fig. 1, uses a duralumin half-cylinder cavity, of radius 50 mm and height 100 mm. A 1 MHz contact transducer is stuck on its back surface and an hydrophone needle is used to record the radiated field in the water. Both sensors are connected to a one channel time reversal electronic driven by a computer. In such cavities, when a source sends a short pulse (a 1.5 cycle of 1 MHz sine wave), the scattered signal spreads over 1000 µs, i.e., 500 times the initial pulse duration. It looks like a signal of a diffused field with a decreasing exponential envelop due to the absorption and radiation.

To illustrate the real time 3D focusing property such impulse responses are recorded in front of the cavity and some of them are reemitted. The focal spot is then moved in real time in front of the cavity. The focusing patterns are shown in Fig.4, on gray scale images extracted from a movie. Each image caracterizes the ultrasonic field and indicates the point source location at four different times. The secondary lobes level depends on the mixing property of the cavity, so that each point has a unique signature. This condition is achieved using a cavity owning both ergodic and chaotic properties[3-4].

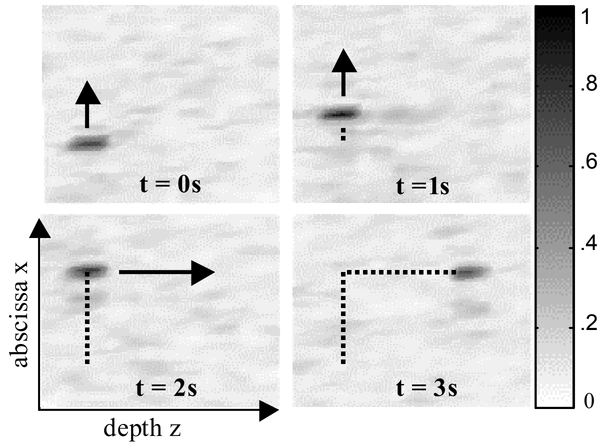

Figure 2: Four images extracted from a movie showing the movement of a pulsing source in the water. The observation area is 5cmx5cm

Synthetic time reversal

The diffraction laws can emerge from the statistic properties. Figure 3 presents the –6 dB width of the field amplitude along a line of the focal plane. Each of these directivity patterns is obtained by focusing ultrasound at distances ranging from 10 to 300 mm. The focusing width Δx variations with depth correctly verify the diffraction theoretical law $\Delta x = \lambda(F/D)$ (λ is the wavelength, F the focusing depth and D the aperture width). Therefore the fit of the experimental measurement of Δx as function of z allows one to deduce apparent diameter aperture. It is found to be equal to D = 95 mm, which is almost the lateral dimension of the front face of the cavity (100 mm). This result indicates that all the conversion of elastic energy inside the cavity into acoustic energy in the focusing domain, is carried out on the whole surface. Now a judicious exploitation of the diffraction on this aperture leads us to define a simpler time reversal protocol: the synthetic time reversal technique based on the Huygens principle.

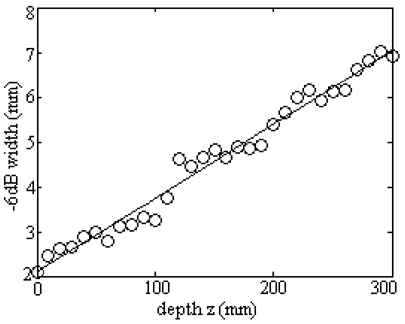

Figure 3: the –6 dB width of focal spot as a function of focal depth

The field on the cavity's front-face is scanned with the hydrophone needle, according to a sampling grid with a spatial step equal to the wavelength (correlation length in a chaotic cavity). Each experimental impulse response is time reversed and then convoluted with a computed free space Green's function. The ensemble of these Green's functions, which corresponds to a point source in the water, obeys to a spherical delay law. Finally a summation over the whole set of signals gives the exact emitted signal able to focus on an arbitrary focal point defined by the free space Green's function. In other words, this "synthetic time reversal process" permits to focus ultrasounds anywhere in a 3D domain, with the time reversal efficiency, just by recording the impulse responses on a 2D surface (the surface of the cavity) instead of a 3D volume (the water in front of the cavity). The focusing system works now like a 2D array: we can realize apodization, beamforming, multi-focusing. The signal to noise ratio of this probe has to be defined.

Contrast

The contrast is defined as the ratio between the intensity of the temporal recompression peak and suraounding signal level. Precedent research [4] have shown the variations of the contrast with time reversal signal duration ΔT and with frequency bandwidth $\Delta\Omega$.

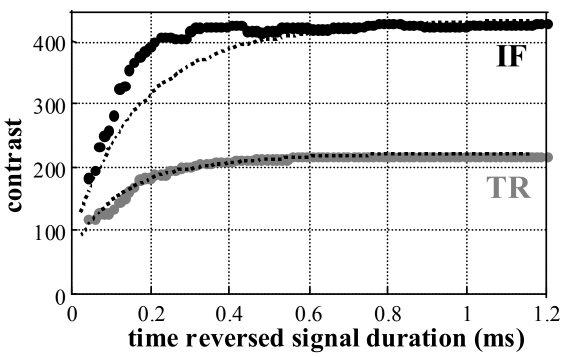

Figure 4: contrast variation with time reversal signal duration for time reversal focusing and inverse filter focusing . The dotted lines present the theory

These contrast variations are well described by a modal theory [Julien de Rosny thesis] based on the two main assumptions: the amplitudes of the vibration eigenmodes of the cavity are uncorrelated and the eigenfrequencies distribution follows a Wigner ditribution for ergodic cavity and Poisson distribution for regular cavity. The theory is based on the decomposition of each impulse response on the base of the eigenmodes of the cavity. The results given by this theory (dotted line) are in perfect agreement with the experimental measurements, particularly for the contrast variation with the signal duration. The two experimental behaviors shown by the gray points on the Fig.4, linear increase and saturation, are depicted by the asymptotic expressions of the theory given by the équation

$$\Delta T << T_H \qquad C \approx \frac{2\Delta\Omega\Delta T}{\sqrt{\pi}}$$

$$\Delta T >> T_H \qquad C \approx 4\sqrt{\pi}T_H\Delta\Omega\frac{\left\langle\alpha^2\right\rangle^2}{\left\langle\alpha^4\right\rangle} \qquad (1)$$

1. The break time between these behaviors is close to the Heisenberg time T_H which is the modal density of the cavity. With an aim to optimize the contrast, the saturation level has to be increased. According to the theory, this level depends on the modal density T_H, which is inherent to the cavity, the frequency bandwidth $\Delta\Omega$, which is limited by the transducer, and the statistic repartition of the eigenmodes amplitudes α. The frequency bandwidth can be artificially increased and the modes repartition can be exploited in an optimal way by inverse filter process. The inverse filter with a single transducer consists in the inversion of eigenmodes energy so that the focusing process takes advantage of the modes of weak energy. The Fig.4 confirms the improvement between the time reversal focusing contrast (gray points) and the inverse filter one (black points).

Conclusion

We have shown the feasibility to focus ultrasounds in real time, on a 3D domain, with a single transducer coupled to a solid cavity and the synthetic time reversal process. The focusing efficiency, the focal width and the signal to noise ratio, are linked to the physical parameters of the cavity and transducer. An inverse filter approach enhance the focusing efficiency and permit the use of any solid as cavity. We hope some future imaging device will work according to this technique[5].

References

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