CONSTRAST ENHANCEMENT IN HARMONIC IMAGING USING CODED WAVEFORMS

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Abstract

Harmonic imaging coupled to the use of contrast agents is a topic of wide interest in ultrasonic medical imaging. Images are built at twice the excitation frequency that corresponds to the resonance frequency of the bubbles embedded in the medium. Consequently, the contrast becomes important between areas of low and high concentration of bubbles. However, at a high mechanical index, the harmonic components of backscattered echoes depends on the intrinsic nonlinear properties of tissues as well as the bubble's resonance. The focused beam is generating harmonics during its nonlinear propagation. It results in a degradation of the harmonic image contrast. Time reversal is an elegant way to find the emission codes allowing us to cancel the harmonic components due to nonlinear propagation of the ultrasonic beam and so to recover an optimal image contrast. Indeed, the wave equation in a nonlinear regime remains time reversal invariant: in the absence of bubbles, if the backscattered echoes are time-reversed and reemitted by the array, the harmonic components of the resulting wavefront are transferred back to the fundamental frequency during propagation. Another way to calculate the optimal waveforms to be emitted for harmonics cancellation consists to achieve the first step of the time reversal experiment using simulations of the nonlinear wave propagation. The waveforms deduced from a KZK or finite differences code can be used as calibrated signals for the in vivo experiments. Experiments conducted with 1D-linear arrays illustrate these cancellation techniques. The contrast enhancement obtained emphasizes the great potential of fully programmable emission boards in multi-channels systems.

I. Introduction

Contrast agents such as bubbles are used to enhance backscattered echoes coming from blood. The injection of contrast agents is combined with nonlinear methods such as harmonic imaging (ultrasound is transmitted at one frequency and received at twice the emission frequency). However, the harmonic content of the backscattered echoes is due to two contributions : first, the bubbles resonance and secondly the natural harmonic generation induced by the nonlinear ultrasonic propagation in tissues. At low mechanical index (M.I.), the harmonic response of bubbles is much higher than the harmonic generation due to nonlinear propagation. However, if ones wishes to increase the transmit signal amplitude (and consequently the M.I.), the intrinsic nonlinearity of tissues becomes non negligible and the harmonics created by sources other than bubbles induce a contrast limitation between bubbly and non bubbly areas.

Recently, Bouakaz and De Jong proposed a very interesting approach for harmonic imaging [1]. Their goal is build the echographic image using higher harmonics instead of the second one. Their technique, called *superharmonic imaging* provides very high contrast images and solves partially the problem of contrast saturation due to intrinsic nonlinearities of tissues. Indeed, for higher harmonics, the ratio between the contribution of bubbles and tissues nonlinearities increases. However, the superharmonic concept is based on the use of new dual frequency array transducers technology for which the beamforming process has to be modified.

The goal of this paper is to propose another way to achieve harmonic imaging at high M.I. using standard probes. In other words, the question is : how can we cancel the harmonics due to nonlinear propagation ? Some years ago, Krishnan *et al* proposed to use a Harmonic Cancellation System (HCS) based on the emission of a signal at twice the fundamental frequency that should cancel the harmonics due to propagation [2]. Their numerical simulations predicted that a 30 dB contrast enhancement could be reached. although they did not make the connection, the underlying concept was based on the invariance of the wave equation in a nonlinear regime. Indeed, a sinusoid propagating in a nonlinear regime is undergoing distortions during propagation. If ones records this signal at a given location, time-reverse it and send it back in the opposite direction, the resulting signal is going to recover progressively its sinusoidal shape. In 2000, Tanter *et al* have shown this effect experimentally [3] and illustrated the breaking of the time reversal invariance after attainment of the shock distance. Recently, we decided to apply the concept of time reversal focusing to harmonic imaging. Time reversal is today a well know concept of linear acoustics for adaptive focusing. However, Time Reversal can also be efficient in nonlinear acoustics. Its application to harmonic imaging allows to cancel the harmonics generation induced by the intrinsic nonlinearities of tissues.

II. Principle of the adaptive harmonic cancellation technique

The basic concept of time reversal invariance in a nonlinear regime is presented in Fig. 1. During propagation, a temporal signal undergoes distortions due to intrinsic medium nonlinearity. Overpressures are propagating faster than underpressure. After some propagation distance, if ones time-reverses the signal and send it back in the opposite direction, the resulting signal is going to recover its initial sinusoidal shape. Indeed, during the backward propagation, overpressures propagate faster than underpressures and overtake their delay. This is due to the time reversal invariance of wave propagation in a nonlinear regime before attainment of the shock distance. Theoretical considerations about this breaking of time reversal invariance can be found in ref [3].

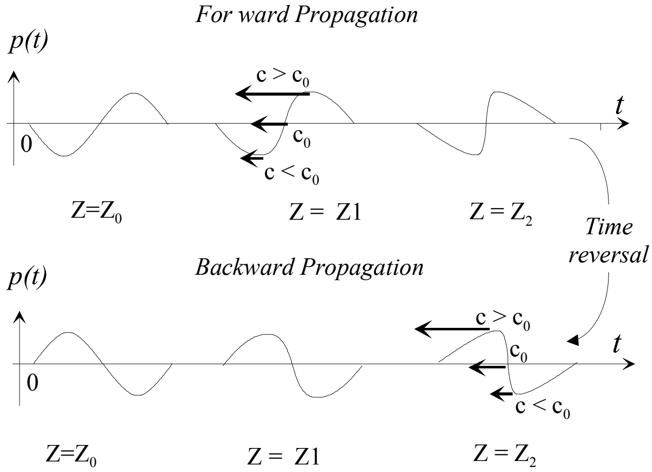

Fig. Time reversal invariance in the nonlinear regime.

How to apply this basic concept to medical applications such as harmonic imaging ? The idea is illustrated in Fig. 2. A first short focused impulse at the fundamental frequency is emitted by the array. The backscattered echoes contains harmonics due to intrinsic tissues nonlinearity. This echoes are received on the array, stored in memories then time-reversed and sent back in the medium. During this backward propagation, the distorted signals focus back in depth and due to time reversal invariance of the wave propagation, the backscattered echoes do not contain any harmonics anymore (see Fig. 2d.).

This concept was validated experimentally using a 1D linear array (Vermon, 128 elements, 4.3 MHz, 0.33 mm pitch). The experiment is achieved in water and the arrray initially focuses on a very thin copper filament located at focus 40 mm away from the probe.

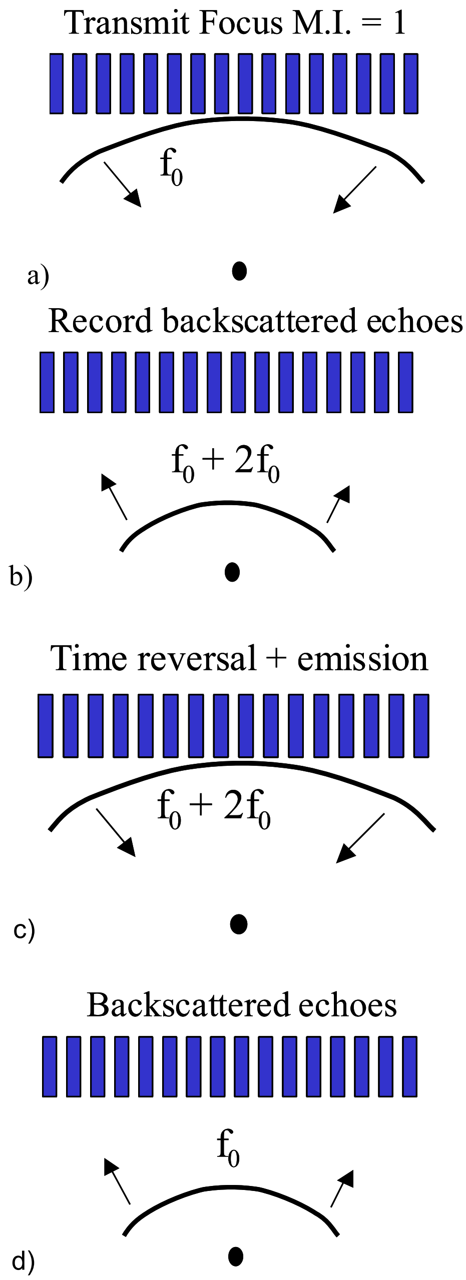

Fig. 2. Principle of the adaptive cancellation of harmonics due to nonlinear propagation.

On the contrary of conventionnal echographic devices, an important point is that we need a fully programmable transmitter for each channel of the system. Indeed, the temporal shape of the emitted signal is the crucial point and conventional 1Bit-emission waveforms can not render the precise details of the optimal emission signals. During the last decade, we developed such fully programmable multichannels systems relying on 128 independent 8 bits linear programmable transmitters (100 V_{pp}, 50 Ohms). One of these systems was used in our experiments to drive the Vermon probe.
The 1D linear array emits a 40 mm depth focused beam with a short impulse presented in Fig. 3a. The

echo backscattered by the filament are received on the array, Fig.3b.

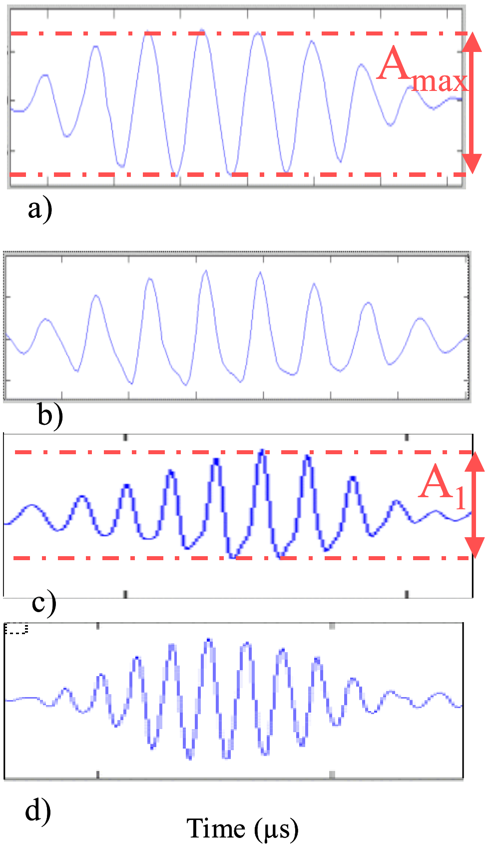

Fig. 3. Experimental results : a) signal emitted by the array; c) backscattered echo after nonlinear propagation in water; c) time reversal and transducer bandwidth correction of the received echo; d) backscattered echo after reemission of the signal presented in Fig. 3.c.

This signal is time reversed after correction of the transducer bandwidth, Fig 3c. This new transmit signal is emitted by the array and the backscattered echo is presented in Fig. 3d. As one can notice, the signal recovered during propagation its initial sinusoidal shape. If we compare the Fourier spectrum of the backscattered echoes in fig3b and fig3d, we clearly see a cancellation of the second harmonic. This harmonic decrease reaches 15 dB.

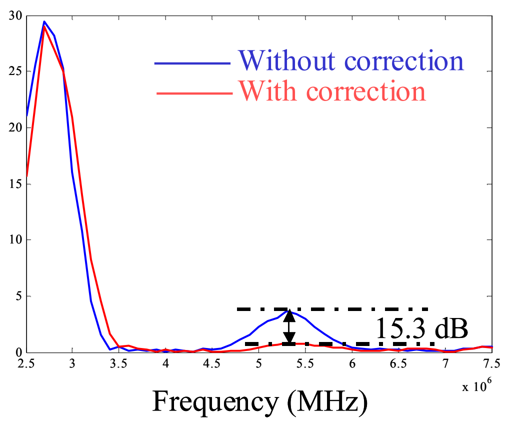

Fig. 4. Spectrum of the backscattered eachoes with and without cancellation of the harmonics by time reversal processing.

As the experiment is achieved in the field of nonlinear acoustics, note that the amplitude A_1 of the transmitted signal has to be carefully chosen. The ratio between the initial transmission amplitude A_{max} and the re-emission amplitude A_1 can deduced during a calibration process, as it is mainly influenced by the difference between the electronic transmission board and the sensitivity of the electronic reception board.

III. A simplified approach using calibrated coded waveforms

The previous approach requires two successive illuminations. The first one allows to acquire information about the nonlinearities of the medium and the second one allows to correct it adaptively. If we assume that tissues nonlinearities are quite homogeneous, The first insonication can be suppressed and replaced by simulations of the nonlinear propagation. These simulations allows to build a data bank of emission signals for different emission amplitudes and tissues nonlinearity parameters. In order to emphasize the potential of this simplified approach, we built such a data bank of signals using the simplest simulation of nonlinear propagation, i.e. the Burgers equation.

We processed echographic images using this data bank of emission signals. The beamforming process in the transmit and receive mode are conventionnal, the only difference consists in the emission waveform applied on each channel of our electronics. Again note that on the contrary of conventional echographic devices, we require a fully programmable transmitter for each channel of the system. Indeed, the temporal shape of the emitted signal is the crucial point.

Figure 5 presents a conventional sinusoidal shaped signal used in harmonic imaging. This emission signal was used in order to produce echographic images of a Agar-Gelatin phantom containing an anechoic inclusion.

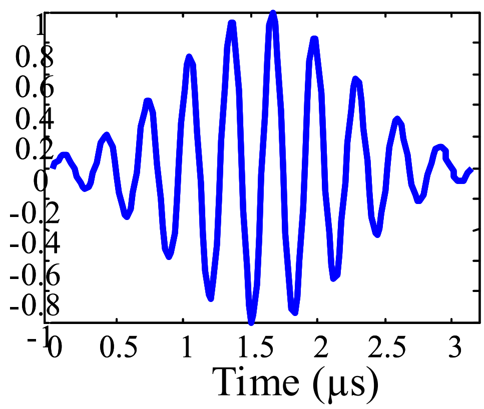

Fig. 5. Conventional emission signal used for the beamforming process of the fundamental and harmonic images of the experimental Agar gelatin phantom presented in Fig. 6.

The fundamental image of the phantom is presented in Fig. 6a and the second harmonic image is presented in Fig. 6b. Although resolution is better, the contrast in the harmonic image is quite poor. The emission signal amplitude was quite high as the M.I. was equal to 1.

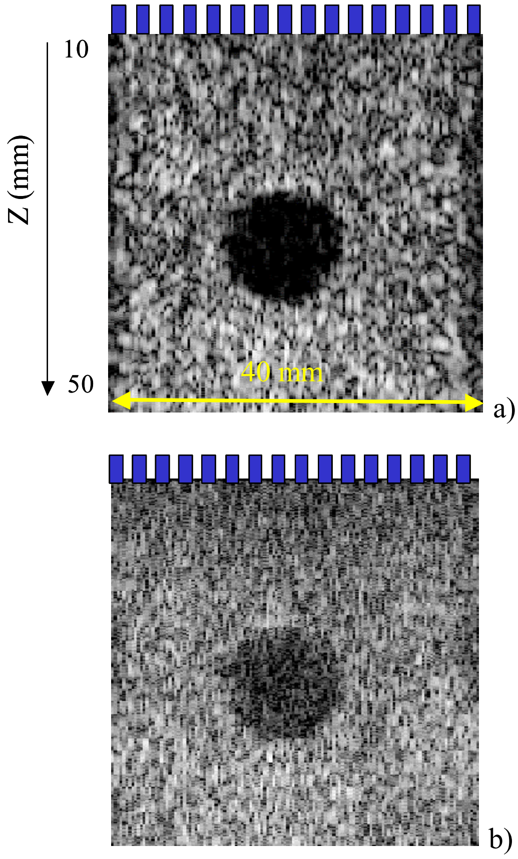

Fig. 6. a) fundamental and b) harmonic image of an Agar gelatin phantom presenting an anechoic inclusion. The contrast in the harmonic image is quite low. M.I. was equal to 1. The probe is working at 4.3 MHz.

The emission waveforms are then progressively modified without changing the beamforming process. The signal is distorted in order to take into account the fact that during propagation overpressures are going to propagate faster than underpressures, see Fig. 7. These signals were computed using a simple finite differences code of the 1D Burgers equation based on MacDonald and Ambrosiano work [4].

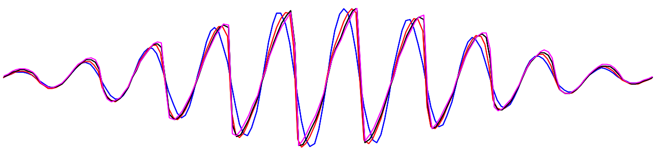

Fig. 7. Emission signals progressively distorted used for the image formation.

The resulting harmonic images are presented in Fig.8. The contrast level of the harmonic image in the agar phantom surrounding the anechoic inclusion progressively disappear. The harmonics due to intrinsic nonlinearity of the phantom are cancelled. Note that a translation of the phantom does not degrade the cancellation ability of the technique.

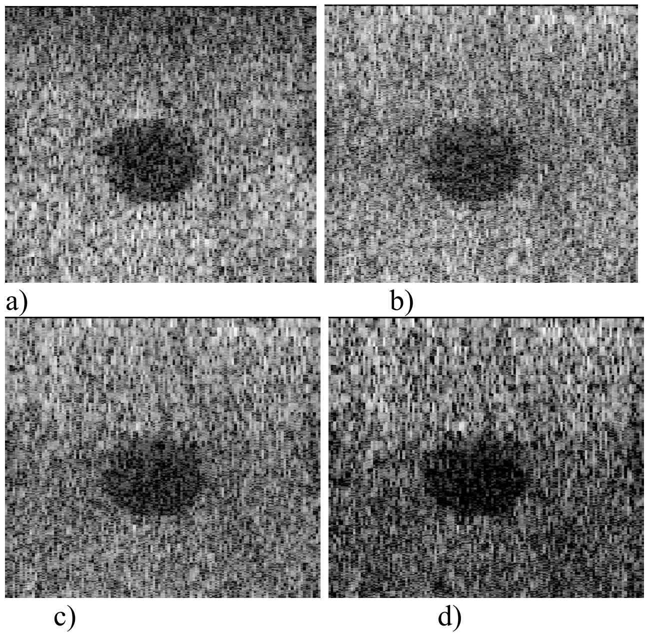

Fig. 8. Experimental harmonic images obtained using distorted emission waveforms. The harmonic content of the agar gelatin phantom surrounding the anechoic inclusion is progressively cancelled.

III. Conclusion

A new way to cancel the harmonics generated during the nonlinear propagation of ultrasound in tissues is proposed. The technique can be adaptive if based on time reversal processing. A simplified approach based on the used of distorted emission waveforms deduced from simulations can also be envisioned. Both techniques require the use of fully programmable transmitter. This paper provides first harmonic cancellation experiments using such a fully programmable transmitter technology. Contrast enhancement is found to reach 15 dB. Further improvements of the technique are in progress. Next harmonic cancellation experiments will be conducted while introducing contrast agents in the medium.

References

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