SPATIAL AND TEMPORAL CONCENTRATING OF ULTRASOUND ENERGY IN COMPLEX SYSTEMS BY SINGLE TRANSMITTER USING TIME REVERSAL PRINCIPLES

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Abstract

In many medical and industrial applications of ultrasound it is necessary to obtain highly localized and short acoustic pulses. The concept of Time Reversal Acoustics (TRA) developed by M. Fink and colleagues provides elegant possibilities of both temporal and spatial concentrating of acoustic energy [1-2]. Based on TRA principles, we investigated possibilities of concentrating ultrasound energy in complex systems using the simplest radiation source with just one piezotransducer. We developed TRA electronic system which provides receiving, digitizing, storing, time reversing and transmitting acoustic signals in a wide frequency range. We used the acoustic reciprocity principle in obtaining the driving Time Reversed signal. Experiments conducted in skull model demonstrated a possibility of significant improvement of TRA focusing by combining an internal (the skull) and external (metal cylinder) acoustic resonators. The phantom experiments confirmed the possibility of efficient temporal and spatial ultrasonic pulse energy concentration by the TRA focusing system.

TRA system with external and internal resonators

The concept of the TRA systems explored in this study is shown in Figure 1. The difference of the tested system from the most of the TRA embodiments described in the literature is that to achieve effective TRA focusing of the ultrasonic beam two parallel sources of reverberation are employed: (a) reverberation due to reflections from the internal and external boundaries in the irradiation media, and (b) reverberations in the additional resonator attached to the transducer.

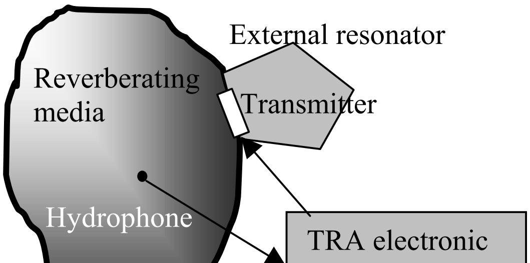

Figure 1. The concept of TRA focusing reverberation media with an external resonator

Step1. An electrical pulse is applied to a transmitter which radiates ultrasonic energy both into the tested media and to the external resonator attached to the transmitter. The initial signal can be a tone burst signal, an r.f. pulse, an amplitude-modulated r.f. pulse, etc.
Step 2. The long reverberated signal is recorded by the hydrophone placed in a chosen point of focusing in the tested media.
Step 3. The recorded signal is time reversed, normalized, amplified and applied back to the transmitter.
Step 4. The TRA focused signal is recorded by a hydrophone. The hydrophone can be moved in the in the vicinity of the focal point to measure the signal spatial distribution.

Experimental setup

Experimental setup used in this study included a TRA electronic unit, several external resonators with different sizes and geometry, and various irradiation media. Electronic unit of the system had the following parameters:

Receiver channel	Transmitter channel
Sampling rates: 100kHz-20MHz Record length: 32000 points Amplitude Resolution: 12 bits Preamplifier with a dynamic range of 10 mV-10V, Frequency band: 1 – 1000 kHz.	Max output of radiation channel: 28V, peak to peak. Dynamic range 60dB Sampling rate: 100kHz - 20MHz Radiation duration: 32000 points Data transfer speed from PC: 1 MB/s

Fig.2 shows the developed electronic unit comprising receiver and transmitter channels. If necessary, a multi channel TRA system can be built by stacking a pile of shown units.

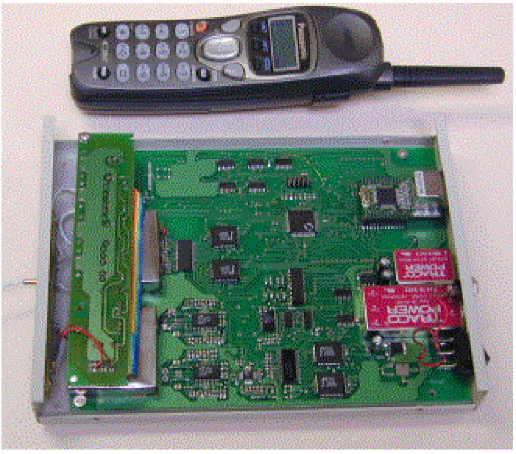

Figure 2. General view of the TRA electronic unit.

Figure 3 shows a few examples of the TRA external resonators used in the study. We tested over a dozen of various resonator configurations. It appeared that the specific shape of the resonator is not a critical issue provided the material it is made of has low absorption of ultrasound (such as e.g. aluminum).

Fig.3. Examples of external resonators

TRA focusing in the skull model

The experiment demonstrating the ability of TRA system with single transmitter to provide high spatial and temporal concentration of the acoustic energy in complex media was conducted in the skull model. A piezoelectric transducer was attached to the external surface of the skull model and an aluminum cylinder was glued to the opposite surface of the transmitter. This cylinder served as an external resonator increasing the reverberation of the radiated signal. The experimental setup is shown in Fig.4. The skull cavity was filled with water. A hydrophone mounted on a 3-D positioning system was used both to measure initial signal for time reversal and to map acoustic field inside the skull.

A triangular pulse (Fig.5a) was applied to the transmitter that radiated short acoustic pulse caused by initial steep front (of the order of 1 microsecond) of the triangular pulse. A long reverberation signal was received by the hydrophone, time reversed and sent back to the transmitter (Fig. 5b). The resulting signal received by the hydrophone is shown in Fig.5c. The spatial distribution of the TRA focused signal energy is presented in Fig.6. Figures 5c and 6 clearly demonstrate the ability of TRA to both temporal and spatial concentrating of ultrasonic energy emitted by a single transducer attached to external and internal resonators.

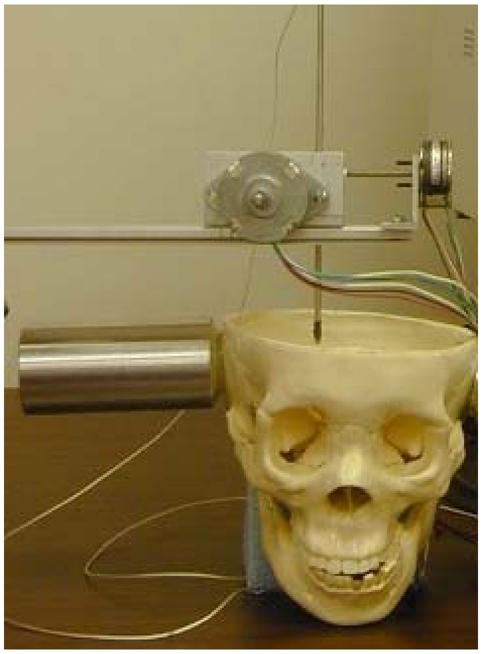

Figure 4. Skull model with an external aluminum resonator and a hydrophone mounted on a 3-D positioning system to map generated acoustic fields

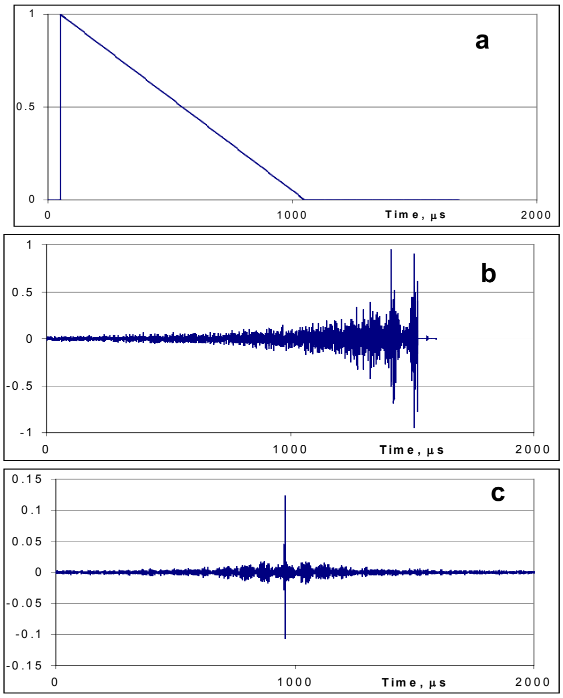

Figure 5. Time tracks of signal for different steps of TRA focusing
a) Initial pulse
b) Time reversed reradiated signal
c) TRA focused signal

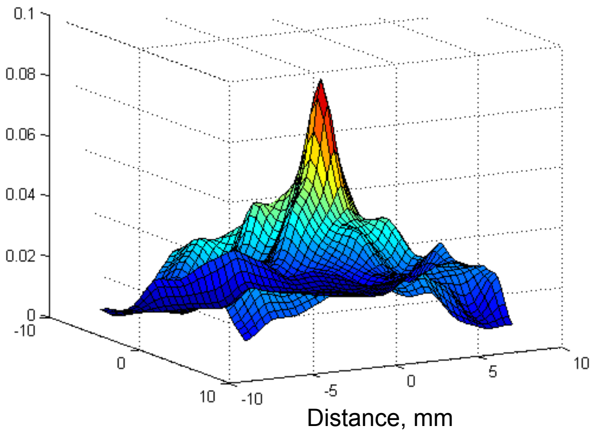

Figure 6. TRA focusing of acoustic energy in the skull model.

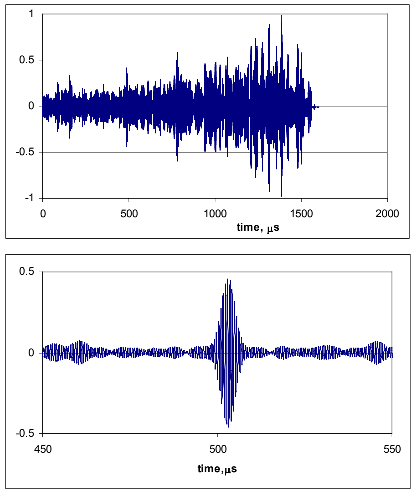

Figure 7. The time tracks for TRA focusing of tone burst signal

a) Time revered signal radiated by the transmitter

b) TRA focused signal

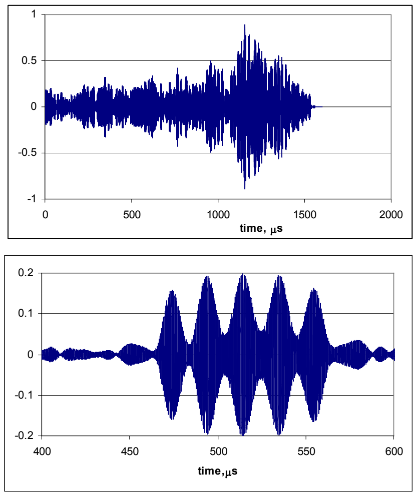

Figure 8. Time tracks for TRA focusing of the amplitude modulated r.f. pulse:
a) Time reversed signal radiated by the transmitter

b) TRA focused signal

TRA based generation of various acoustic waveforms

In various medical applications of ultrasound it is necessary to focus different acoustical waveforms. TRA focusing of ultrasound, illustrated above in Figs 5 and 6, was made using short electrical pulse signals. Equally efficient TRA focusing can be achieved for tone burst signals and amplitude-modulated signals. Experiments presented in Fig.7 -Fig.10 illustrate this possibility. The experiments were conducted using a single piezoceramic transducer attached to a metal resonator radiating into a small water tank. Figure 7 illustrates TRA focusing of a tone bust signal radiation. The initial pulse was a Gaussian tone burst signal with carrier frequency of 750 kHz. Fig.7a shows the time reversed reradiated signal. The duration of this signal is about 1500 µs and the duration of TRA focused signal presented in Fig.7b is about 10 µs. This significant temporal compression allows concentrating acoustic energy near the focus point.

Several medical applications of ultrasound are based on the use of the acoustic radiation force [3-5]. Specifically, using the radiation force of the amplitude modulated ultrasonic beam it is possible to generate low frequency shear waves in soft tissues and realize the so called Shear Wave Elasticity imaging [3]. We explored possibilities of generating amplitude modulated signal by the TRA focusing system. Figure 8 illustrates the results of these experiments. The initial signal was an r.f. pulse with a carrier frequency 750 kHz and amplitude-modulated with a frequency of 50 kHz. The reradiated time reversed signal and TRA focused signals are shown in Fig.8.

Overlapping TRA focused pulses

In several medical applications of ultrasound, especially in therapeutic and surgery applications, it is necessary to deliver significant energy to the region of treatment. Short ultrasonic pulses separated by long off time, such as those illustrated above, will not be of any use in the application where the amount of delivered energy is of key importance. We investigated the possibility of improving the duty cycle of the TRA based ultrasonic irradiation system. One of the possibilities of increasing total ultrasonic energy delivered by the TRA focusing system is to use overlapping TRA pulses. We conducted several experiments on generation of TRA focused ultrasonic signals in a wide range of pulse repetition rates. Fig.9 illustrates some of the results of that study. The initial signal was a tone burst signal in a Gaussian envelop with carrier frequency of 1.84 MHz. Pulse repetition rate was varied from a single pulse to a series of overlapping pulses generated with 8 µs intervals.

Figure 10 shows spatial distribution of ultrasound intensity for 8 and 40 microsecond pulse repetition intervals. It is seen that the spatial distribution does not depend on the time interval between pulses. The main conclusion from the experiments illustrated by Figs 9 and 10 is that the TRA focusing efficiency does not deteriorate even in highly overlapping time reversed pulses.

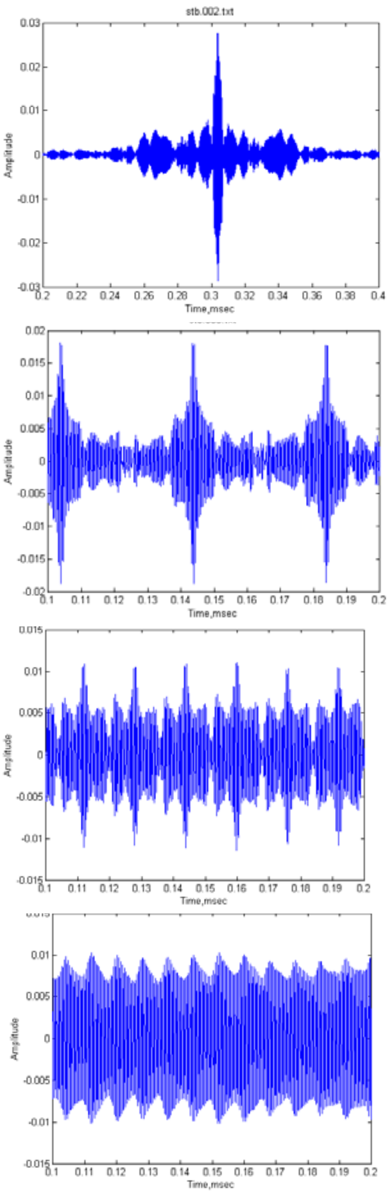

Figure 9. TRA focused signals for with different pulse repletion rates

a) Single pulse

b) Repetition interval 30µs

c) Repetition interval 16µs

d) Repetition interval 8µs

Concluding remarks

Focusing of ultrasonic energy is fundamental aspect of both diagnostic and therapeutic ultrasound. The most obvious advantage of TRA focusing of ultrasonic energy in comparison of that made with the use of conventional phased arrays is incomparable simplicity of the hardware required to achieve the goal. The focal area of the TRA system could be much more localized compared with that of a conventional ultrasound focusing system. TRA focusing system provides greater flexibility in generating arbitrary ultrasonic waveforms in the focal region.

Acknowledgment

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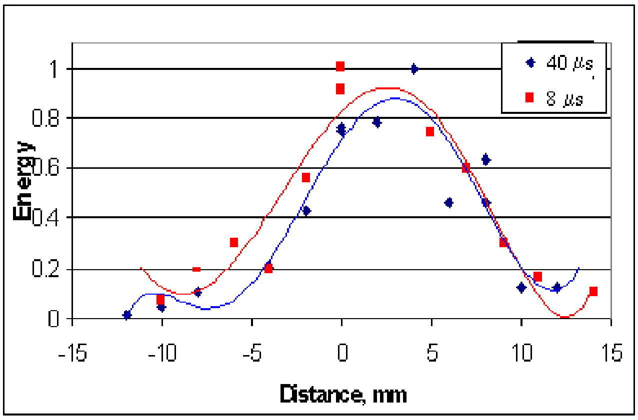

Figure 10. Spatial distribution of acoustic intensity in TRA focused signal for two pulse repetition rates

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