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Evaluation of a Time Reversal Technique for Low Frequency Acoustic Measurements in a Reverberant Tank

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The objective of this work is to validate the efficiency of a recently proposed technique for acoustic measurements of transducer response. This technique allows measurements to be done in a reverberant tank at considerably lower frequencies than the limit imposed by free-field conditions. The method is based on time reversal, a concept originally developed for sound propagation in marine environment, that performs signal deconvolution with a very little amount of data processing. It was seen that the method can be used to focus at a fixed point a transmit pulse several ms long, allowing calibrations down to the low kHz range in a 3-4 m tank. Early investigations already showed that the focusing of the acoustic field depends on the frequency. In this work, further measurements were done at the new tank facility of the Underwater Acoustics Laboratory at the Istituto di Acustica "O. M. Corbino" to evaluate the accuracy of the results.

1. Introduction

Measurements of transmit and receive voltage sensitivities of underwater transducers are commonly performed in a water tank using pulsed signals. Continuous wave signals generate interference patterns, due to multiple reflections by the rigid boundaries and the free surface that may add more or less coherently, and the measured frequency response deviates from the true response. The trasmit pulse length is limited by free-field conditions, which impose a maximum value equal to the delay of the first reflection with respect to the direct wave. This value depends only on the geometry of the tank: for medium-high frequencies it is generally long enough to include a sufficient number of cycles in the received pulse in order to make precise measurements. For frequencies below 10 kHz, the limit imposed by typical tank dimensions may decrease the number of cycles down to 3-4 only. Transducers operating at low frequencies often have higher Q, and a steady state response is not reached before the end of the pulse. As a result of these limitations, the minimum allowed frequency turns out to be a function of both tank dimensions and transducer Q [1].

Several methods have been investigated to overcome this frequency limit, from the early interference smoothing and prediction [2,3] to more recent signal modelling [4,5]. A new approach has been recently proposed based on time reversal [6]. This method, also called phase conjugation, was first developed for marine acoustics [7] and has recently found applications in acoustical imaging [8] and sound propagation in shallow sea [9].

The main feature of time reversal is to eliminate the distortion of a wavefront emitted by a point source and travelling through an aberrating or reverberating medium by reversing its direction of propagation, thus restoring the original wavefront at the source location. Theoretically, for a perfect reconstruction, the pressure field should be recorded at each point on a closed surface enclosing the source; normally this is not possible and the field is sampled using an array of finite size. Under a controlled environment such as a reverberant water tank, it is however possible to obtain satisfactory results even sampling the pressure field at a single point.

The purpose of this work is to examinate the validity of this method for reducing reverberation noise in measurements of low frequency transducer response. Due to the more relaxed free-field conditions, compared to earlier tests [6], a comparison with standard techniques becomes now possible down to lower frequencies.

2. Theoretical considerations

The concept of time reversal can be described in terms of a simple model of acoustic propagation. We consider two reciprocal transducers A and B placed inside a rectangular tank with perfectly reflecting boundaries and a free air-water interface. We assume both transducers to be omnidirectional, as it is usual for frequencies of the order of a few kHz. The transmit and receive sensitivities are assumed to be constant in the frequency range of interest. We also assume that the boundary conditions do not change with time, and that the sound velocity is constant. The tank impulse response $h(t)$, for a particular tank shape and positions of A and B, is defined as the signal received by B when A sends a unit impulse. This signal will be the superposition of the direct pulse and a series of time delayed pulses corresponding to the multiple arrivals of the transmit pulse reflected by the boundaries. Under spherical wave spreading, the pulse amplitudes will be inversely proportional to the distance, i.e. to the delay time. If A transmits a generic signal $x(t)$, the signal $y(t)$ received by B may be expressed in terms of the impulse response, that is:

$$y(t) = x(t) \otimes h(t), \qquad Y(f) = X(f)H(f),$$

where $\otimes$ indicates convolution, and X, Y, H are the Fourier transforms of x, y, h respectively. If $y(t)$ is reversed in time and transmitted backwards from B to A, provided that the tank impulse response did not change, one obtains:

$$z(t) = y(-t) \otimes h(t),$$

$$Z(f) = X(-f)H(-f)H(f) = X^*(f)|H(f)|^2.$$

The last passage is valid since $x(t)$ and $h(t)$ are real. Therefore, the output signal $z(t)$ received by A is the convolution of the original input signal $x(t)$, reversed in time, with the autocorrelation of the impulse response $h(t)$. If the impulse response is sufficiently irregular, its autocorrelation will exhibit

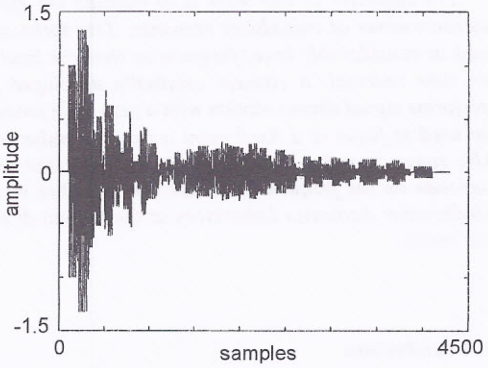

Fig. 2. Theoretical forward signal.

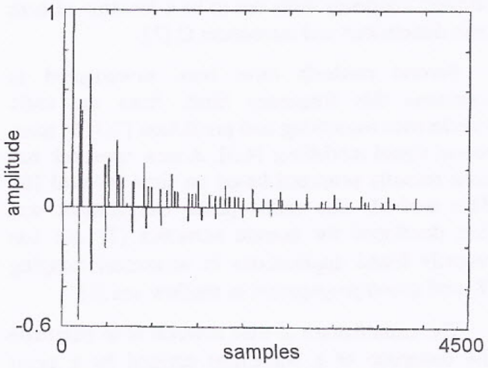

Fig. 1. Simulation of a tank impulse response.

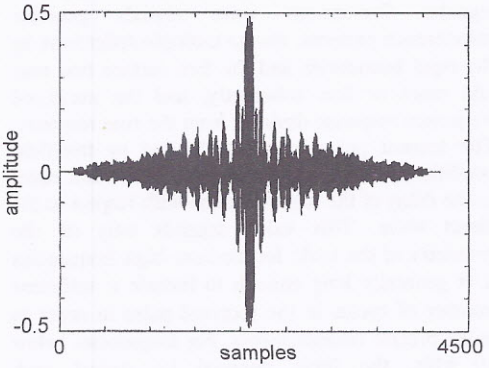

Fig. 3. Theoretical backward signal.

a sharp peak at t=0 surrounded by sidelobes of relatively small amplitude, and the output $z(t)$ of the time-reversed signal will closely approximate the input signal $x(t)$. The degree of approximation is given by the randomness of the impulse response, since any repetitive pattern in the time distribution of the reflected pulses will generate higher sidelobes.

The effectiveness of time reversal is based on the fact that the impulse response of a typical water tank is usually quite complicated, since it may consist of a large number of multiple reflections from the walls, the bottom and the free surface. As an example, consider Figure 1 showing a simulated impulse response of a rectangular tank. Figure 2 shows the forward signal $y(t)$, obtained as the convolution of the impulse response of Figure 1 with a 10-cycle sinusoidal burst. Figure 3 shows the backward signal $z(t)$, being the convolution of the time-reversed $y(t)$ with the impulse response. The size of $z(t)$ is twice the impulse responce plus the size of $x(t)$, and the original burst is reconstructed in the central part of the signal.

3. Experimental setup

The time reversal method was tested in the newly established tank facility at the Istituto di Acustica. The tank is 6 m long by 4 m wide, with a 5.5 m water depth. Free field condition for gated continuous wave measurements give a low frequency limit of 2.5 kHz for a transducer Q of 5.

One omnidirectional projector and one hydrophone were mounted on two separate rigs at 1.5 m distance and 2.5 m depth, and their position was chosen so that the multiple arrivals of reflected waves were distributed in time as evenly as possible. This was done placing the transducers closer to one of the tank walls, so that the travel time of reflections from opposite walls would differ appreciably.

Figure 4 shows the block diagram of the experiment. A transmit pulse from the projector is recorded by the hydrophone (forward signal): this signal is reversed, retransmitted by the projector using an arbitrary waveform generator and recorded again (backward signal). Truly speaking,, the method requires that the backward signal be transmitted exchanging the transmit and receive positions. However, there is no difference if the signal is transmitted from the same position, since the multiple paths travelled by the acoustic waves are the same in both cases. This simplifies considerably the experimental setup, since there is no need for a reciprocal transducer to receive and transmit the backward signal from the same point.

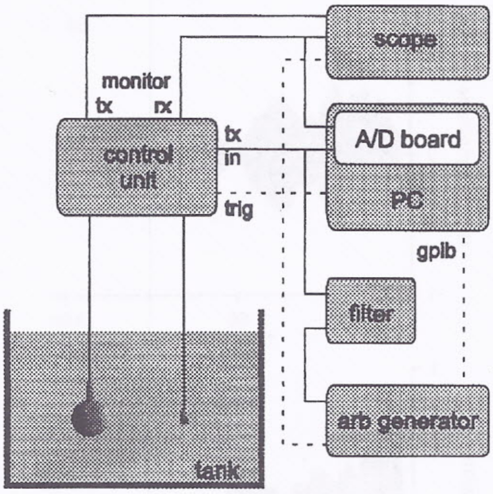

Fig. 4. Block diagram of tank experiment.

The transmit pulse was generated by a control unit using direct digital synthesis with 12-bit D/A converter. Pulse width was set to 12 ms with an envelope risetime of 1.5 ms: an example is shown in Figure 5 for a frequency of 1.5 kHz. The transmit signal was sent to an omnidirectional projector, with a typical transmit response of 150 dB at 11 kHz resonance. The forward signal was recorded by omnidirectional hydrophone with receive response of -205 dB up to 80 kHz and acquired on a PC using a 12-bit A/D board with a maximum sample rate of 100 kHz. The signal was time reversed on the PC, downloaded to a 10-bit arbitrary waveform generator, and sent to the transmit signal input port of the control unit after bandpass filtering from 100 Hz to f+500 Hz with f equal to the transmit pulse frequency. The size of the acquired forward signal was limited to 1024 samples, equal to the record

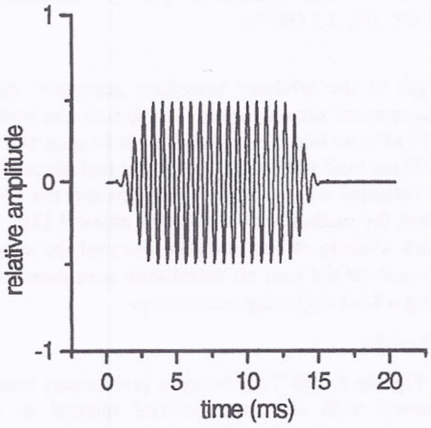

Fig. 5. Transmit pulse, frequency = 1.5 kHz.

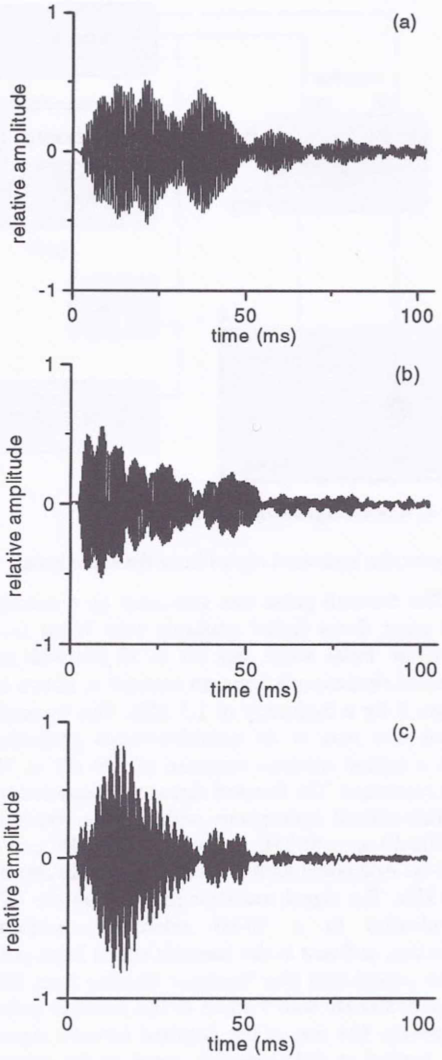

Fig. 6. Forward signals for frequency = 1.5 kHz (a), 2.5 kHz (b), 3.5 kHz (c).

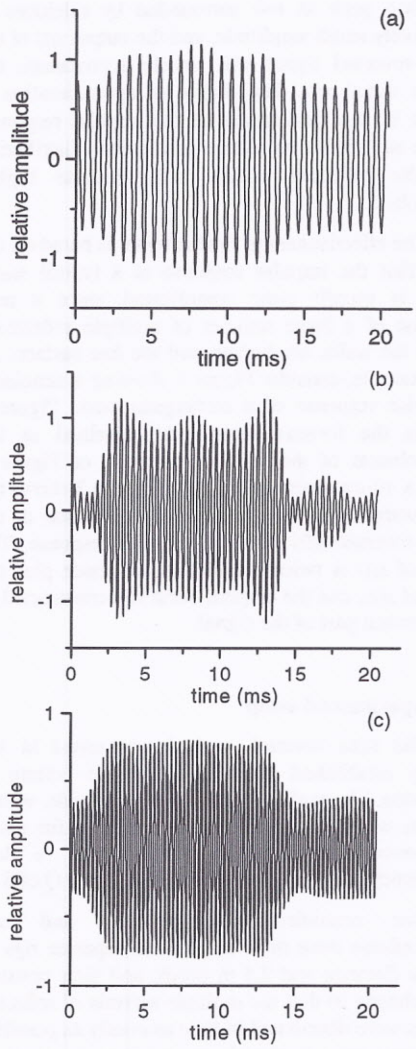

Fig. 7. Backward signals for frequency = 1.5 kHz (a), 2.5 kHz (b), 3.5 kHz (c).

length of the arbitrary waveform generator. As a consequence, the maximum sample rate was limited to 10 kHz, so that the acquisition could span at least a 100 ms time window, necessary to include most of the reflected waves. Such limitations did not allow to test the method for frequencies above 4 kHz, for which aliasing effects severely distorted the signal. Throughout the test, all waveforms were monitored using a 8-bit digitizing oscilloscope.

4. Results

Figures 6 and 7 show some preliminary results obtained with the time reversal method in the experiments described above. The forward signal is represented in Figures 6 a,b,c for frequencies of 1.5 kHz, 2.5 kHz and 3.5 kHz respectively. These signals were reversed and retransmitted, and the corresponding backward signals are shown in figures 7 a,b,c. The reconstruction of the original transmit pulse shape is visible in figures 7 a,b,c showing the central portion of the recorded signal, to be compared with the transmit pulse in Figure 5.

From the analysis of Figures 6 it can be seen that the time window is not sufficiently large to include even the smallest reflections. This is one of the reasons for the imperfect reconstruction of the transmit pulse. A few attempts were made to extend the time window by lowering the sample rate for frequencies below 2 kHz, but this did not give a great improvement, due to the corresponding loss of details in the envelope of the forward signal.

The pulse shape in Figures 7 is not constant, but changes with frequency. This effect may be explained considering interference phenomena due to the difference in travel paths between the direct and the reflected wave. If the time delay between the arrivals of two multiple reflections is equal to $(n-1/2)T$, with $n=1,2...$ and $T=1/f$, then the two waves can interfere destructively in the overlap region. This is noticeable if one of the first reflections is in phase opposition with the direct wave: the resulting forward signal exhibits a sudden drop in amplitude. The same happens if the first reflected wave from the free surface, which has a reversed sign, is delayed by $t=nT$. When the shape of the initial part of the forward signal is irregular, due to these effects, the operation of time reversal may give poor results. This seems to be an inherent limitation of the method when only one transmit point and one receive point are employed. The reconstruction of the transmit pulse is not complete for all frequencies within a specified range, if the transducers are kept in the same positions.

Future investigations should be carried out for the extension of this technique to multi-element transducers, like an array or even a small set of discrete reciprocal elements acting simultaneously, to implement an acoustic mirror.

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