CALIBRATION OF UNDERWATER TRANSDUCERS USING A TIME REVERSAL METHOD

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1. INTRODUCTION

Calibration of underwater transducers is generally performed in a tank facility using gated-CW methods, due to the presence in the received signal of multiple echoes reflected by the tank walls and the free surface. The trasmit pulse length is limited by free-field conditions, which impose a minimum value for the delay of the first echo with respect to the direct wave. In the frequency range below 8 - 10 kHz, the limit imposed by the tank dimensions may lower the number of cycles down to a maximum of 3 - 4. If the transducer Q at the same frequency is higher than this number, the transducer response cannot reach steady state before the end of pulse, and measured data are affected by errors. As a result of these limitations, the minimum allowed frequency turns out to be a function of both the tank dimensions and the transducer Q [1, 2].

Several methods have been investigated to overcome this frequency limit, from the early interference smoothing and prediction [3, 4] to more recent signal modeling [5, 6] and transient suppression [7]. The approach followed here is of a novel type, and is derived from a formulation of "Matched signal" processing which was originally developed for marine environment [8].

The purpose of this work is to investigate the feasibility of this method for transducer calibration in a water tank in the range 3 – 8 kHz, which is generally performed by other means. For frequencies below 3 kHz, a calibrator for line-hydrophone arrays is available, which however cannot be used with transducer sizes greater than 10 cm [9]. It is therefore desirable to extend this method below 3 kHz, and possibly down to 1 kHz.

2. THEORY

We consider the propagation of an acoustic wave between two points, namely one projector and one hydrophone, inside a rectangular tank with perfectly reflecting boundaries and a free air-water interface. 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 projector and hydrophone, is defined as the signal received by the hydrophone when an ideal pulse drives the projector. This signal will be the superposition of the direct pulse and a series of 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. A generic signal $y(t)$ received by the hydrophone may be expressed in terms of the impulse response, i.e.:

$$y(t) = x(t) \otimes h(t) \quad \text{or} \quad Y(f) = X(f)\,H(f)$$

where $\otimes$ indicates convolution, and X, Y, H are the Fourier transforms of x, y, h respectively. If this output signal is time reversed and transmitted backwards between the same two points, provided that the tank impulse response did not change, one obtains:

$$z(t) = y(-t) \otimes h(t) \quad \text{or} \quad Z(f) = X(-f)\,H(-f)\,H(f) = X^*(f)\,|H(f)|^2$$

The last passage is valid since *x(t)* and *h(t)* are real. Therefore, the output signal *z(t)* 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 a sharp peak at t=0 surrounded by sidelobes of relatively small amplitude, and the output of the time-reversed signal will approximate closely the input signal. 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.

3. MODEL OF TANK RESPONSE

To visualize the effect of time reversal, a simple model of the tank impulse response was created. For arbitrary transmit and receive positions, the travel times of multiple reflections from opposite surfaces were computed, assuming a constant sound velocity. The reflection coefficient was chosen to be 1 for rigid boundaries and –1 for the free surface. Also multiple reflections between the two transducers were included, assuming a reflection coefficient of 0.25. For simplicity, multiple reflections involving adjacent surfaces were neglected, and only up to the first 15 reflections for each pair of surfaces were considered. The impulse response was obtained setting $h(t_i) = d_0/d_i$ and assuming a unit amplitude pulse for the direct wave (travel path d_0) and spherical spreading.

Figure 1 shows a typical impulse response obtained with this model. Figure 2 shows the forward signal, obtained as the convolution of the impulse response of Figure 1 with a 10-cycle sinusoidal burst. Figure 3 shows the backward signal, as a result of convolution of the time-reversed forward signal with the impulse response. The original burst is reconstructed in the central part of the signal, as it is visible in Figure 4 where the time base has been enlarged.

If the frequency of the burst wave is varied, occasionally some peaks in the impulse response cancel out, their waves being out of phase. In this case, the shape of the forward signal becomes irregular, as it is shown in Figure 5. If this signal is time reversed, the output looses much of the information on the original signal: Figure 6 shows the result of time reversal for the signal of Figure 5. This aspect of the focusing will be discussed in the next section.

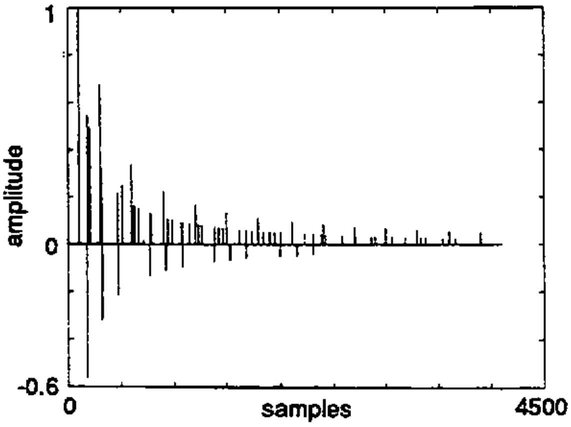

Figure 1. Model of tank impulse response

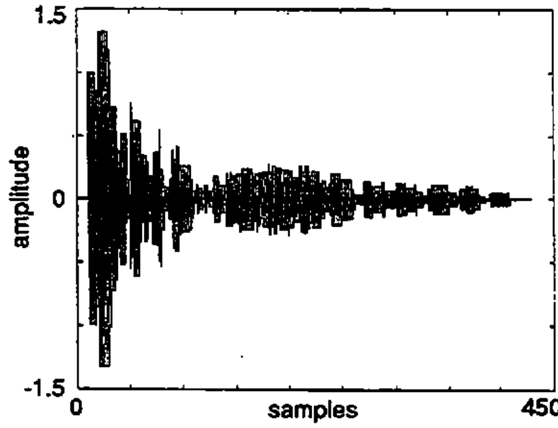

Figure 2. Forward signal, 10-cycle tone burst convolved with impulse response of figure 1.

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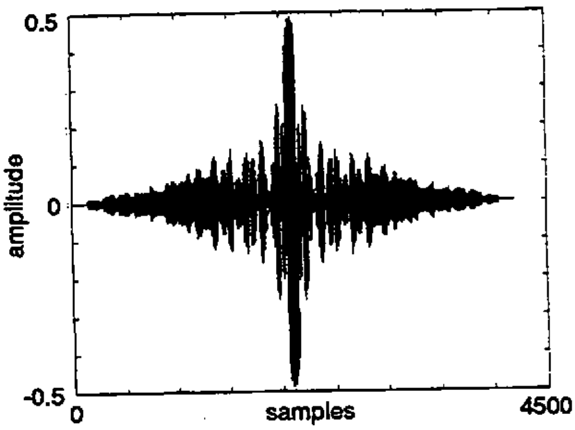

Figure 3. Backward signal obtained transmitting backwards the time-reversed signal of figure 2.

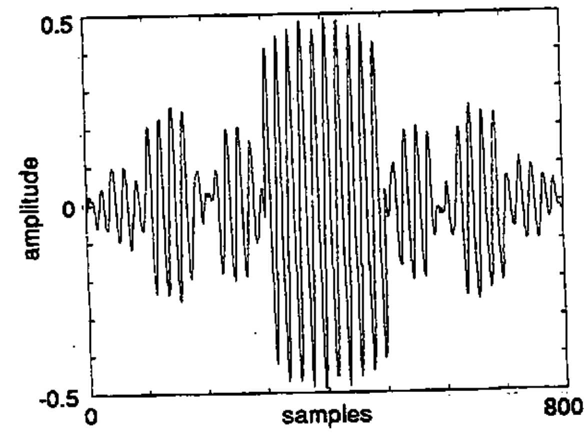

Figure 4. Central portion of backward signal of figure 3 showing pulse reconstruction.

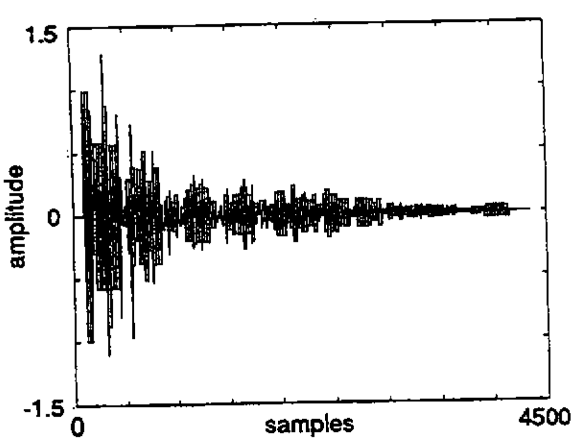

Figure 5. Forward signal, same as figure 2 for a different frequency.

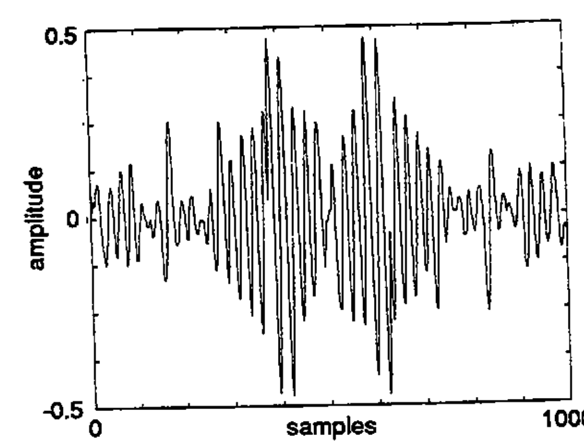

Figure 6. Central portion of backward signal obtained from signal of figure 5.

4. EXPERIMENTAL SETUP

A series of tests have been carried out at the tank facility available at SACLANTCEN, to investigate the possibility of using the time-reversal method for lowering the usable frequency range in the calibrations. The tank dimensions are: 4.5 m length, 3.6 m width, 2.3 m depth. For gated-CW technique the frequency limit imposed by these dimensions is approximately 5 kHz, assuming a transducer Q of 3.

A PC Pentium 133 running under Windows 95 was used in the experiment, together with the following instrumentation: HP 33120A function/arbitrary waveform generator, Nicolet 430 3-channel 12-bit digitizing oscilloscope, Stanford SR560 low-noise preamplifier, Wavetek 753A Brickwall filter, Bruel & Kjaer 2713 power amplifier.

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In the most general case, the method of time reversal requires the use of two projectors and two hydrophones. However, in these experiments three transducers were employed: one projector , one reversible transducer and one hydrophone (device under test). The projector and the hydrophone were closely mounted in the same rig with a separation distance of a few cm. The reciprocal transducer was mounted in a separate rig at a distance of 1 m approximately. Initially, the projector transmits a tone burst that is recorded by the reciprocal transducer. This signal is acquired in binary format by the scope and is transferred to the PC, where it is converted into Volts and time reversed. Finally, it is downloaded to the waveform generator and retransmitted backwards by the same reciprocal transducer from the same position. The time-reversed signal travels the same multiple paths as the forward signal and is received by the hydrophone, which is mounted close to the projector. If the impulse response of the tank did not change, and if the distance between the projector and the reference hydrophone is small compared to the wavelength, the shape of forward signal will be reconstructed when all multiple reflections have reached the hydrophone coherently. To ensure that all significant reflections were included in the time reversed signal, its duration was determined measuring the reverberation decay and adjusting accordingly the burst repetition frequency.

The transducer position was chosen to distribute as evenly as possible the reflected pulses: this was done by placing either the projector or the hydrophone at a shallow depth, of the order of 40 cm, and off the center of the tank. In this way the travel times of the first reflection by opposite surfaces are quite different, and the corresponding pulses in the impulse response are more distributed. Also, it was attempted to find relations giving optimal positioning, but this turned out to be dependent on a large number of parameters in a complicated way. As a general rule, symmetrical positions, as half depth or center of tank, were shown to be more critical and to generate smaller focusing regions.

Two methods were used to transmit backwards the time reversed signal. The signal from the power amplifier was fed alternatively into the projector and the reciprocal transducer, leaving the transducer positions unchanged. Another way to reverse the transmission was to mount one projector and one hydrophone on a "Y" shaped structure mounted on a turntable, so that a 180-degree rotation was equivalent to an exchange of projector and hydrophone positions. In the second case, low frequency non-reciprocal projectors can be used, with higher trasmitting sensitivity.

4.1 Transducers

The following reciprocal transducers were used in the experiments:

Type	F 40	ITC 1032	B&K 8100	Reson TC4034
Used as	Proj/hydr	Proj/hydr	Hydrophone	Hydrophone
Resonance f	17 kHz	32 kHz	80 kHz	300 kHz
Receiving Sensit.(@ 5 kHz)	-190 dB	-195 dB	-206.0 dB	-216.8 dB

Even if the B&K and Reson are reciprocal, their transmit sensitivity is too low in the frequency range below 10 kHz, and can be operated effectively only as hydrophones. Throughout the experiments, the receiving sensitivities of B&K and Reson hydrophones were assumed to be flat in the entire frequency range.

4.2 Data acquisition

In all measurements, a gated tone burst was sent as a forward signal, and the peak value of the received backward signal was measured in the portion containing the focused burst. A frequency band ranging approximately from 1.5 kHz to 6 kHz was chosen. The signal received by the hydrophone was bandpass filtered, the highpass frequency being 500 Hz and the lowpass frequency approximately twice the transmitted frequency. This was found to be a good compromise between narrowband, which gives less noise, and wideband, which gives a better focusing. If the band is narrowed, a higher burst count has to be used to prevent the shape of the transmit pulse to be distorted. On the other hand, if the band is widened beyond the resonant frequency of the projector, the transient response amplitude may be several dB higher than the steady-state response, and it becomes difficult to obtain a clear focusing at a frequency different from the resonant one of the proiector.

The waveform generator was used to output the sinusoidal burst as the forward signal, with a typical burst count of 30 - 40 cycles and a repetition rate of 2 Hz. The signal amplitude of the generator output was typically 1 Vrms, and the B&K power amplifier gain was set to 30 dB. The signal formed by the superposition of the direct wave and all multiple reflections was acquired with the scope, setting the sweep length to 160 or 320 ms, which for a record length of 16,000 samples gives a sample rate of 100 kHz and 50 kHz respectively. The scope was triggered by the waveform generator, and was operated in average mode to increase signal-to-noise ratio; the number of waveforms averaged was between 4 and 8. The acquired signal, after being reversed in time on the PC, was downloaded to the signal generator as an arbitrary waveform. The generator was programmed to output a single waveform with the same rate as the forward signal.

4.3 Focusing

Initially, the ITC and F 40 were placed alone in transmit and receive positions to check the focusing of the time-reversed signal. After receiving the forward signal, projector and hydrophone connectors were swapped and the time-reversed signal was sent back and monitored while displacing the hydrophone position along the three directions. The focusing region was found to be approximately spherical and to depend on the frequency. Ideally, the reconstruction of the transmitted pulse takes place only in one point: at different locations, the reflected waves coming from different directions interfere incoherently. Indeed, it was seen that there is only a small coherence region, which can be of the order of a few cm only at frequencies above 5 kHz. The size of this coherence region could also depend in a more complicated way on the transducer size and shape. For frequencies of less than 5 kHz this effect was not important, and the positioning of transducers did not seem to be critical. At frequencies of approximately 2 – 3 kHz it was possible to displace laterally one of the transducers by several cm without a significant change in the shape of the focused signal.

If the time delay between the arrival of two multiple reflections is equal to $(n-½)T$, 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 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 a delayed by 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. In general, for given projector/hydrophone positions, a number of "notch" frequencies were observed for which the method fails. To overcome this, a possible suggestion is to use an array of source/receiver transducers to realize a time-reversal mirror as it has been demonstrated in laboratory [10] and in the ocean [11].

The duration of the transmitted pulse could be varied without affecting the results. For a frequency of 5 kHz, a burst length up to 64 cycles was employed (12.8 ms duration) with no significant change in the focusing; a typical value of 32 (6.4 ms) was chosen.

When the frequency is lowered below 1 kHz, it was seen that the interference pattern disappears in the forward signal. In these conditions the wavelength is large enough compared to the differences in travel time between reflections, so that the first ones add almost coherently with a small phase shift. Also, the burst duration becomes comparable to the tank reverberation time: in these conditions, the acoustic waves in the tank are almost stationary, and the concept of time reversal itself looses its significance.

4.4 Transducer setup

Two types of arrangements were employed to validate the method. A calibration by comparison was performed to measure the receiving sensitivity of one of the two reciprocal transducers (F 40) and one of the hydrophones (B&K or Reson).

A) One reference hydrophone (B&K) was placed close to one of the two projectors (F 40). The forward burst was transmitted with F 40 and received by ITC. The backward signal was then retransmitted by ITC and recorded with both F 40 and the B&K. In this way, both the ITC and F 40 were used as projectors and hydrophones. However, at frequencies lower than 2 –3 kHz the ITC showed a very low transmit sensitivity and the resulting signal-to-noise ratio was poor. Another disadvantage is that the two projectors have different sensitivities, and the driving voltage has to be adjusted each time the signal is reversed.

B) Two reference hydrophones (B&K and Reson) were placed approximately 5 cm apart on one end of the Y shaped mount. On the other end, the F 40 projector was placed in a symmetric position, so that a rotation of 180 degrees was performed to swap the acoustic center of the projector and the midpoint between the hydrophones. This setup allowed using the F 40 for transmitting both ways, which was better at low frequencies. The focusing was seen to be accurate only up to 6 – 7 kHz, since for higher frequencies the separation distance between the two hydrophones was greater than the size of the focusing region. Also a mutual influence of the two hydrophones was expected due to their finite dimensions.

During the experiment, also other projectors were tested (ITC 1007, ITC 3013, J-9) but were discarded mainly because their resonant frequency was too close to the frequency range in use. In some cases, the high transducer Q rendered difficult to drive effectively the projector away from resonance.

5. RESULTS

Using setup A, the receiving sensitivity of the F 40 was measured by comparison with that of B&K reference in the frequency range 800 Hz – 5 kHz. The projector/hydrophone distance was 90 cm, and depth was 80 cm (F 40 and B&K) and 65 cm (ITC). No particular care was taken in choosing the X and Y positions, except for avoiding symmetrical ones (center of tank). Burst count was 64 cycles, giving a variable pulse length between 13 and 80 ms, according to the wave frequency. The burst repetition rate was 2 Hz, and acquisition time was 160 ms. The input bandpass filter cutoff frequencies were 1 kHz and 8 kHz for frequencies above 2 kHz; they were set to 0.5 f and 2 f for frequencies below 2 kHz. The power amplifier was fed with a 1 Vrms amplitude signal, and the output gain was set to 30 dB. The total gain in the receiving circuit (preamplifier gain and filter gain) was 36 dB.

Figure 7 shows the result of measurement with setup A, together with the reference calibration data available for the F 40 projector. The error is within 1-2 dB, except around 3.5 kHz, possibly because of interference problems. It was seen that between 3.5 and 4 kHz a change in transducer position of the order of 50 cm caused a shift in the measured value of the order of 3 dB.

Setup B was used to measure the receiving sensitivity of the Reson hydrophone using B&K as a reference. F 40 was used to transmit both the forward signal and the time reversed signal, after a 180-degree rotation of the turntable. Depth was 160 cm for all three transducers, while other parameters were the same as in the previous measurement.

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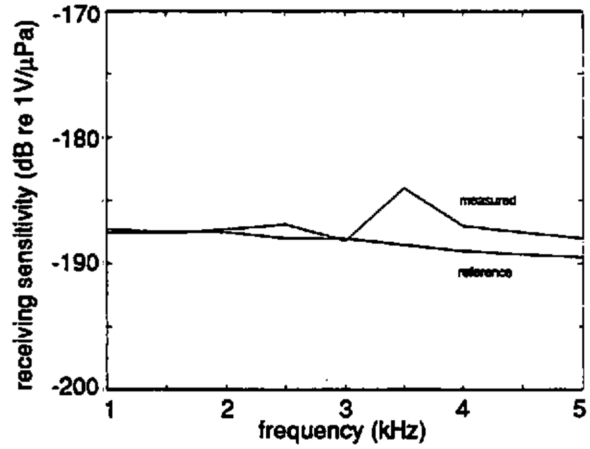

Figure 7. F40 calibration by comparison with B&K 8100: measured data and reference data.

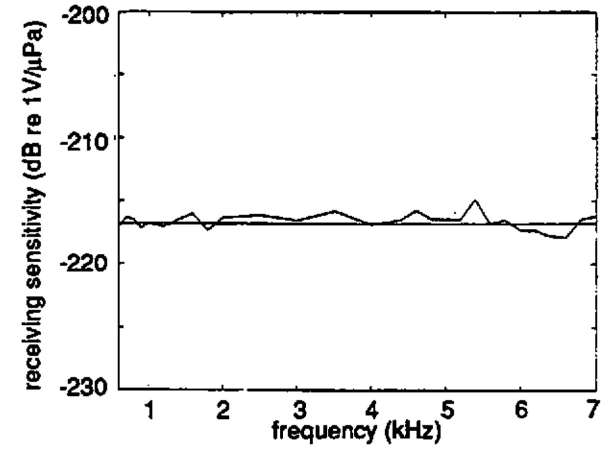

Figure 8. TC4034 calibration by comparison with B&K 8100: measured data and reference data (straight line).

Figure 8 shows the result of measurement with setup B. The horizontal segment represents the calibration value available for the Reson hydrophone. The measured data reproduce the flat frequency response of the hydrophone within ±1.5 dB.

6. CONCLUSIONS

The present work showed that a time-reversal focusing method could be employed to overcome the frequency limit imposed by free-field conditions for calibrations in a water tank. With this method, a transmit pulse of longer duration than with normal gated-CW methods can be used, and the time reversal acts as a deconvolution, removing the multiple reflections and restoring the original pulse shape. The method has a number of advantages: it is independent of the tank size and shape; it can be used for frequencies down to the order of one kHz and it performs better for lower frequencies; it is easy to perform and requires very little data processing. On the other hand, it can be used only in a relatively narrow frequency band, and for some frequencies where reflections interfere destructively, the results are not completely satisfactory. To test the method, two transducers were calibrated using a reference hydrophone of known sensitivity, and the results showed an error of 1–1.5 dB. The method does not seem to be suitable for high-accuracy calibrations, but it could be useful for a quick check of the order of magnitude of the response of some unknown transducer.

A further step that may improve the degree of accuracy of this method could be the use of a different system for waveform acquisition allowing greater accuracy and a higher number of data samples. We are currently working on a new system set-up based on a commercial data acquisition board for the PC equipped with Analog-to-Digital and Digital-to-Analog Converters, a large data memory and a processor running under a real-time operating system. This system will perform the calibration without the use of expensive instruments and the necessity of trained operators.

7. REFERENCES

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