PHASE CONJUGATION FOR UNDERWATER ACOUSTIC COMMUNICATIONS

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In this paper a multipath problem in shallow water acoustic channel and phase conjugation technology will be presented. Acoustic communications in shallow water had been a difficult problem due to the characteristics of the underwater acoustic channel. The shallow water channel is the environment which is of particular interest to many research workers and presents a number of challenges to the designers of communications systems. Underwater acoustic channels are characterized by multipath phenomenon whose characteristics are time varying. This is the major factor that limits underwater acoustic communications performance. Communication systems can be categorized as using either incoherent or coherent modulation strategies. This paper presents the phase conjugation technique, also called "time-reversal", which is the subject of active research in many areas of acoustics. This is a new method for coherent underwater acoustic communication. Preliminary results confirm the potential utility of the phase conjugation in underwater acoustics with applications in underwater communications. This method effectively mitigates the multipath propagation and can be used to solve this problem.

INTRODUCTION

Over the last decade, acoustic phase conjugation or time reversal has generated steadily growing interest in the underwater research community. TRM was originally developed using ultrasound in air. This method has numerous applications in medicine, non-destructive testing, geophysics, and now in underwater acoustics. A series of carried out ocean acoustic experiments confirming the robustness and potential utility of time reversal mirrors in underwater acoustics with applications in active sonar and underwater communications. Time reversal method has application in shallow water in the area of active sonar [4], the echo-to-reverberation enhancement [5], and reverberation nulling [5, 6]. In time reversal acoustics a signal is recorded by an array of transducers, time-reversed, and then retransmitted into the medium. The retransmitted signal propagates back through the same medium and refocuses approximately on the source.

TRM compensate for the multipath propagation that is common in sea acoustics and that limits the capacity of underwater communications systems. The problem occurs in shallow water where sound travels as though in a waveguide. Acoustic signals in shallow water normally interact repeatedly with both the sea surface and bottom. A time reversal mirror in an ocean waveguide consists of a vertical line array of receivers and transmitters. A probe signal is transmitted from a source at distance. The received signal display a complicated arrival structure involving many multipaths specific to the shallow water waveguide. When the received signals are time reversed and retransmitted into the sea, the sea combines the individual multipaths to produce a signal close to the original transmitted signal at the probe source location. For underwater acoustic communications multipath arrivals cause interference between symbols resulting in symbol errors. Sometimes an adaptive filter is used to remove such multipath signal. However if many multipath signals are received, even an adaptive filter cannot remove all of them. Using the sea to combine the multipath arrivals via a time reversal process is a natural way to conduct underwater communication [1]. The reflected and refracted waves are converged to focus in space and time and the signal level received at the focus increases and the symbol interferences are reduced.

In the frequency domain, time reversal is equivalent to phase conjugation, which takes advantage of reciprocity, a property of wave propagation in a static medium and a consequence of the invariance of the linear wave equation to time reversal [2]. Phase conjugation is an environmentally self-adaptive process that can find application in localization and communication in complex sea environments [3].

Time reversal is a novel form of acoustic communication that is based on spatial reciprocity and time symmetry of the wave equation. At the focal point, time reversal compresses dispersive acoustic energy both in time and space. The temporal compression recombines the dispersive multipaths reducing intersymbol interference. The spatial focus of the time reversal process moderates the effect of channel fading. Therefore, the receiver would not need spatial diversity. These two properties point at time reversal as a potential method for communication [3].

1. THE BASIC THEORY OF THE PHASE CONJUGATION TECHNIQUE

Phase conjugation is synonymous with time reversal in the time domain. This is a two-way communications technique that first measures the channel response with a PS, and then transmits back the reversed communication sequences. Time reversal method can be seen as implementing a matched filter of the impulse response of the waveguide. Signal x(t) is transmitted from a source in a waveguide, and this signal is convolved with the impulse response of the waveguide $h_i(t)$, and the signal $y_i(t)=x(t)*h_i(t)$ is received on the i-th element of the array of N source/receive transducers (SRA). The SRA receives $y_i(t)$ and retransmits the time reversed version of the signal, $y_i(-t)$. In this way time reversal implements a linear matched filter giving the autocorrelation of the impulse response of the waveguide. The signal received back at the original source location can be written as:

$$x_r(t) = \sum_{i=1}^{N} x_i(-t) * \left(h_i(-t) * h_i(t)\right) \tag{1}$$

This equation shows that quality of the time reversal focus depends on the number of echoes received and the number of SRA elements N. Fig.1 shows the basic geometry for phase conjugation technique. A probe source sends out a pulse of sound. The array of source/receiver elements records the complicated arrival structure. The dispersed signal with all its multipath structure is time reversed and retransmitted by SRA into the sea. The acoustic energy converges to the original PS depth and range. A vertical receive array (VRA) is collocated with the PS to measure the vertical structure of the acoustic field.

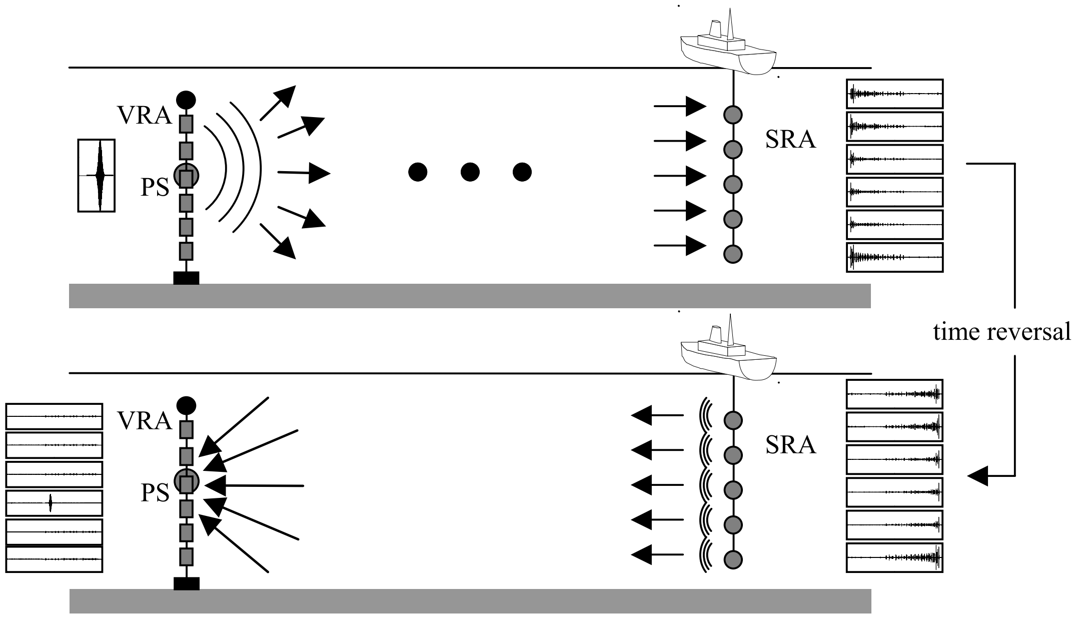

Fig.1 Basic geometry for phase conjugation technique

2. MATHEMATICAL FOUNDATIONS OF THE PHASE CONJUGATION

In this section the basic of mathematical formulations of phase conjugation in range-dependent model will be presented [8]. Probe source is located a distance R from the source/receive array. Point source emits a time-harmonic wave of angular frequency ω, which is determined from the Helmholtz equation:

$$\nabla^2 G_\omega(r;z,z_{ps}) + k^2(z) G_\omega(r;z,z_{ps}) = -\delta(r - r_{ps})\ \delta(z - z_{ps})\ ; \qquad k(z) = \frac{\omega}{c(z)} \tag{2}$$

A monochromatic point source with frequency ω located at (r_{ps},z_{ps}) generates an acoustic pressure field that may be decomposed into a sum of normal mode functions:

$$G_\omega(r;z,z_{ps}) = \frac{ie^{(-i\pi/4)}}{\rho(z_{ps})\sqrt{(8\pi\, r)}} \sum_n \frac{\phi_n(z_{ps})\phi_n(z)}{\sqrt{k_n}} e^{(ik_n r)} \tag{3}$$

where k_n are the modal wave numbers and $\phi_n(z)$ are the eigenfunctions of eigenvalue problem defined by the ordinary differential equation:

$$\frac{d^2\phi_n}{dz^2} + [k^2(z) - k_n^2]\,\phi_n(z) = 0 \tag{4}$$

The mode functions satisfy the depth eigenvalue equation at every range point and are ortonormal, i.e.:

$$\int_0^\infty \frac{\phi_m(z)\phi_n(z)}{\rho(z)} dz = \delta_{nm} \tag{5}$$

and have a form:

$$\sum \frac{\phi_n(z)\phi_n(z_s)}{\rho(z_s)} = \delta(z - z_s) \tag{6}$$

The phase conjugation process consists of exciting the SRA sources by the complex conjugate of the received field $G_\omega^*(R;z_j)$. The resulting acoustic field transmitted from the J sources in SRA satisfies the wave equation:

$$\nabla^2 P_{pc}(r,z) + k^2(z) P_{pc}(r,z) = \sum_{j=1}^{J} \delta(z - z_j) G_\omega^*(R;z_j,z_{ps}) \tag{7}$$

The solution of (7) is the volume integral of the product of the Green's function as specified by (2) and the source term of (7). For a vertical line of discrete sources, the integral reduces to a sum over the source positions:

$$P_{pc}(r,z;\omega r = \sum_{j=1}^{J} G_\omega(r;z,z_j) G_\omega^*(R;z_j,z_{ps}) \tag{8}$$

The data are given by $G_\omega(R;z_j, z_{ps})$ and the replica field by $G_w(r;z,z_j)$. $P_{pc}(r,z)$ focuses at the position of the probe source (R,z_{ps}) that was demonstrated by substitute (3) into (8), which specifies that over all modes and array sources are summed:

$$P_{pc}(r,z;\omega) \approx \sum_m \sum_n \sum_j \frac{\phi_m(z)\phi_m(z_j)\phi_n(z_j)\phi_n(z_{ps})}{\rho(z_j)\ (z_{ps})\sqrt{k_m k_n r R}} e^{i(k_m r - k_n R)} \tag{9}$$

In case of an array which spans the almost whole water column and actually samples most of the modes, the sum of sources may be approximate as an integral and satisfy the orthonormality condition (5). In this case the sum over j selects out modes m=n and the equation (9) simplifies to:

$$P_{pc}(r,z;\omega) \approx \sum_m \frac{\phi_m(z)\phi_m(z_{ps})}{\rho(z_{ps}) k_m \sqrt{rR}} e^{ik_m(r-R)} \tag{10}$$

3. ACOUSTIC COMMUNICATION USING PHASE CONJUGATION

A possible application of phase conjugation technology is underwater acoustic communication. For phase conjugation communications, the signal from the probe source, received on the source receiver array (SRA), will be time reversed, modulated with a signaling scheme (e.g. BPSK) and transmitted into the sea. The signal arriving at the probe source location should be free of intersymbol interference and the message can then be extracted from the received data by simple demodulation. The main disadvantage of this method is that it requires the establishment of a two way link. For phase conjugation communications to work, the ocean needs to be stationary from the time the probe signal is transmitted from the probe source to the time the back-propagated signal is received by the probe source. A new probe signal will be required every time the ocean environment changes.

Phase conjugation can be implemented in either an active or passive mode. For communication purposes, the main difference between active and passive implementations is the direction in which the information flows. In the active case, information can be sent from the array to a distant source, while in the passive case the source sends information to the array.

Active phase conjugation is the communication from array to point. It has been implemented in the sea and has also been proposed as a method for communication [3, 7, 8]. In this technique pulses are transmitted from source and next received at each element of the SRA and time reversed. This time reversal pulses are multiplied one by one with the symbols of digital data sequence and in this way time reversal signals are composed. These signals are retransmitted from each element of the SRA, and then they converge to the focus point. In this time reversal signals transmitted from the SRA, time-reversal pulses are superimposed at a symbol rate, so that the signal received at the focus is the sequence of pulses without multipaths. That is almost the same as the data sequences to be sent. Fig.2 showed the active phase conjugation process.

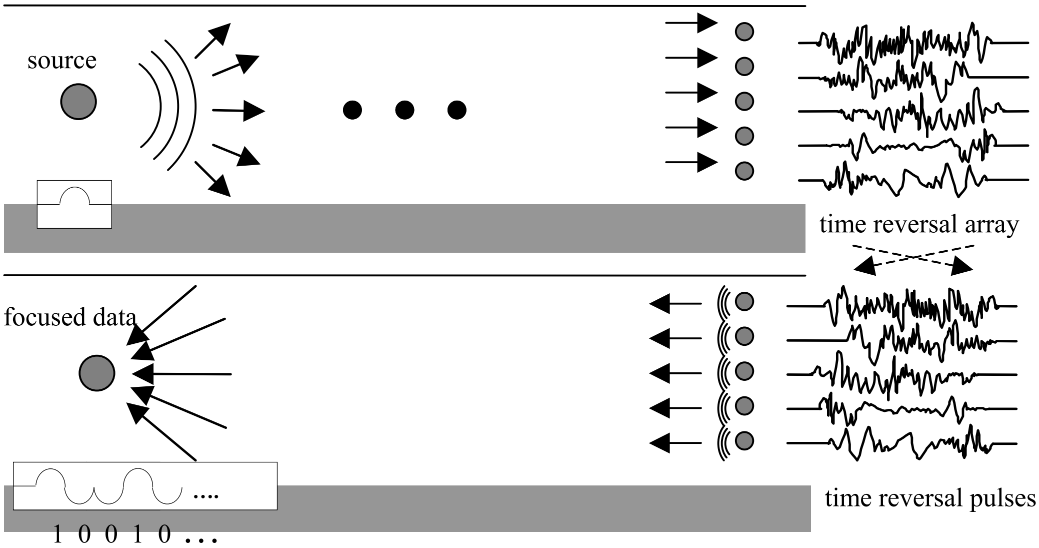

Fig.2 Active phase conjugation process

Another way to achieve multipath combination is to use passive phase conjugation. As a method for communication this procedure is passive in that the array need only receive signals and does not need to transmit. Passive-phase conjugation for underwater communications is carried out as follows. The process begins with transmission of a single probe pulse from the distant sound source and reception of the response at each element of the array. The data stream is then transmitted by the sound source and recorded by each element of the array. The signal processing step involves cross correlating the probe receptions and data streams as observed at an array element. This cross correlation is done in parallel at each array element and the results are summed across the array to achieve the final communication signal ready for demodulation. As the ocean changes, it becomes necessary to break up the data stream by inserting new probe pulses [1]. The passive phase conjugation process is shown in Fig.3.

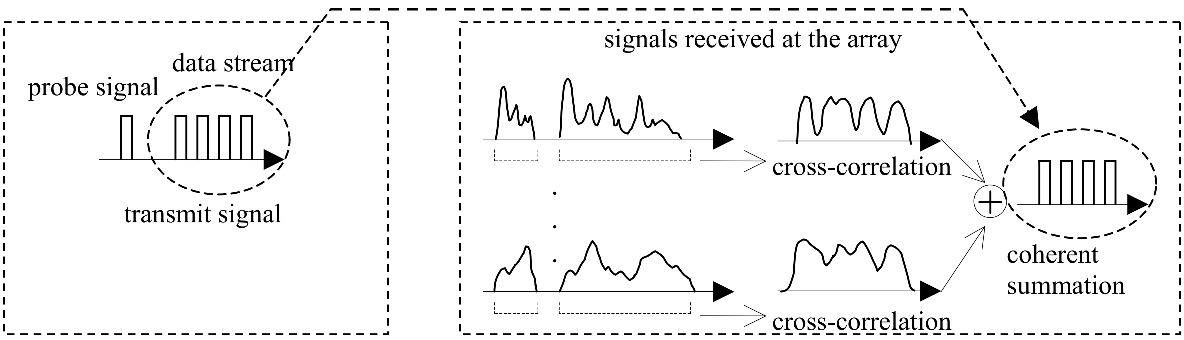

Fig.3 Passive phase conjugation process

The probe pulse and the data stream transmitted by the source are showed at the left side of the Fig.3. At the right side there are the probe and data stream which are observed at each of the elements in the receiving array. The true power in the technique comes from using the spatial diversity provided by the array. The cross-correlations are then coherently summed across the array.

4. CONCLUSIONS

This paper presents the properties of the phase conjugation process. This method can have application in active sonar and undersea communications. Phase conjugation technique potentially is an effective underwater acoustic communications technique that reduces channel fading in shallow water and effectively deals with intersymbol interference originating from multipath time spread. This method is a stand alone system that requires no computationally intensive algorithms. In case of underwater communications phase conjugation provides a possibility to implement space-time multiplexing in complicated underwater environment.

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