Research on the Focusing Property of Time Reversal Waves with Various Array Configurations

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Abstract

In this study, the focusing property of time reversal waves was verified through tank experiments and simulations, and it is investigated how the configuration of the Time Reversal Array (TRA) affects the focusing property. It was concluded that time reversal waves enable a desired acoustic signal to be converged to the focus. Further, the simulation results qualitatively concurred with the experimental results. And the following matters were clarified: If the TRA is tilted or the heights of its elements are invariably shifted individually, the signal received at the focus is not disrupted. Even a horizontal TRA can generate time reversal waves if it is of adequate length. The signal received at the focus is not disrupted when the number of elements of the TRA is reduced.

1. Introduction

In recent times, extensive research has been conducted on time reversal waves (phase conjugate waves) in ocean acoustics [1-4]. Time reversal waves enable a desired signal to converge to the focus, even in unknown and inhomogeneous media. As time reversal waves converge to a “point” at any range, their focusing property is quite different from waves focused using the conventional beam forming method. In other words, using time reversal waves is equivalent to collecting the reflected and refracted waves that are removed as unnecessary signals in the beam forming method. In this study, tank experiments and simulations were conducted to study the properties of these waves in shallow water, and how the configuration of the TRA elements affects the focusing property was investigated.

2. Acoustic field by TRA

By using the vertical TRA allocated as shown in Fig. 1, time reversal waves in shallow water are generated as follows. First, an acoustic signal is transmitted from a source at \( r_s = (r_s, z_s) \), and this signal is received by the TRA whose \( n \)th element is placed at \( r_n = (r_n, z_n) \). The signals are “time reversed” and retransmitted from each element of the TRA. These time reversal waves converge to the focus where the “original source” exists.

The acoustic field of time reversal waves at the arbitrary point \( r = (r, z) \) is expressed, as follows:

\[
G_{in}(r, r_s) = \sum_{n=1}^{N} G^*(r_n, r_s) G_n(r, r_n) \tag{1}
\]

Here * indicates a complex conjugate and \( G(r_2, r_1) \) indicates the Green function from \( r_1 \) to \( r_2 \).

3. Tank Experiments

3.1. Outline of the experiments

As shown in Fig. 2, the tank experiments were performed in the shallow part (L6×W9×D0.6 (m)) of the anechoic tank at JAMSTEC to simulate conditions of shallow water. The transducers are ITC 1042, which is omni-directional. The wave transmitted from the source is a burst pulse, 10 waves of a 100 kHz sinusoidal wave. The acoustic signals are sampled at 1 MHz in both AD and DA converting.

3.2. Experimental results

The signal received at the 3rd element, as a representative, of the TRA is shown in Fig. 3 when tone burst signals are transmitted from the source. These received signals also include the waves reflected from side-walls.
When the time reversal waves of these signals are transmitted from the TRA, the signals received at the focus and at neighboring points are shown in Fig. 4. The focus is at \( r = (0, 0.3) \) (m). These figures reveal that at the focus, the burst pulse is received at a very high SNR, while at the neighboring points, the pulse does not appear. Thus, it is clarified that, spatially, the time reversal waves converge very sharply.

3.3. Comparison with the simulation results

The Pekeris solution of the normal mode method was used as the simulation method.

Shallow water was modeled in the Pekeris model as shown in Fig. 1. In this model, water depth \( H \), sound velocity and density in water and at the sub-bottom, \( c_1, \rho_1, c_2, \) and \( \rho_2, \) respectively are all constant. The thickness of the sub-bottom is considered infinite and the transversal waves at the sub-bottom are ignored.

Under these conditions, the transfer function from a source \( r_s = (r_s, z_s) \), to an arbitrary receiving point \( r = (r, z) \), at angle frequency \( \omega \) is as follows[5]:

\[
G_m(r, r_s) = \frac{2}{H} \sqrt{\frac{2}{\pi |r - r_s|}} \sum_{n=1}^{\infty} \left[ A(k_m) \times \sin(\beta_1 z) \sin(\beta_2 z) \exp \left( -k_m (r - r_s) - \frac{\pi}{4} \right) \right],
\]

\[
A(k_m) = \frac{1}{\sqrt{k_m}} \times \frac{\beta_1 H}{\beta_2 H - \sin(\beta_1 H) \cos(\beta_1 H) - b_2 \sin^2(\beta_1 H) \tan(\beta_1 H)},
\]

\[
\beta_1 = \sqrt{\frac{\omega^2}{c_1^2} - k_m^2}, \quad \beta_2 = -j \sqrt{k_m^2 - \frac{\omega^2}{c_2^2}}, \quad b = \frac{\rho_1}{\rho_2}.
\]

Here, \( k_m \) is the horizontal wave number of the \( m \)th mode, and \( \beta_1 \) and \( \beta_2 \) are the vertical wave numbers in water and at the sub-bottom, respectively. The attenuation modes are not considered in this paper. The value of \( k_m \) is obtained as a solution of the following characteristic equation:

\[
\beta_1 \cos(\beta_1 H) + j b \beta_2 \sin(\beta_1 H) = 0
\]

Calculation results simulating tank experiments are shown in Fig. 5. In the experimental results, the time reversal waves include waves reflected from the side-walls. Since the normal mode calculation does not simulate such reflected waves, it is meaningless to quantitatively compare Fig. 4 and Fig. 5. However, qualitatively, the simulation results resemble those of the tank experiments, because the pulse is received clearly, and around the focus the pulse disappears in both results.

4. Effect of TRA Configuration

4.1. Effect of TRA Tilting

It is supposed that the vertical TRA is installed by tensioned mooring in the ocean. In practice, however, it is expected that the moored array is inclined due to currents or ocean waves. Therefore, Tank experiments and simulations were conducted to study how the tilting of the TRA affects the focusing property.

In real-scaled simulation, the depth of the water is 100 m, an original source is placed at \( r_s = (100, 50) \) (m), the distance between the source and the TRA is 5,000...
m, and \( c_1, \rho_1, c_2, \) and \( \rho_2 \) are 1,500 m/s, 1,000 kg/m\(^3\), 1,600 m/s, and 1,500 kg/m\(^3\), respectively. The length of the TRA is 100 m and the interval between its elements is 1.5 m. The original signal transmitted from the source to the TRA is 500Hz burst pulse. These settings are used in all real-scale simulations described in this paper.

The length of the TRA is 100 m and the interval between its elements is 1.5 m. The TRA was inclined at 5.0 degrees to the side of the focus. Figure 6(a) shows the one of the experiment results, in which the TRA was inclined at 5.0 degrees to the side of the focus. Figure 6(b) shows the results of real-scale simulations in which the TRA was inclined at 30.0 degrees. These figures demonstrate that time reversal waves can converge when the TRA is steadily inclined.

Tank experiments and simulations in which the TRA was dynamically, rather than steadily, tilted were conducted as follows: When the signals from the source were received at the array to generate the time reversal waves ("receiving process"), it was tilted to the side of the focus. The array was then tilted to the opposite side when the time reversal waves were transmitted from the array ("retransmitting process"). Results of an experiment, in which the tilting angle was \( \pm 2.5 \) degrees, are shown in Fig. 7(a). Results of ocean-scale simulations, in which the tilting angle was \( \pm 0.6 \) degrees, are shown in Fig. 7(b). These figures show that the tilting of the array between the "receiving" and "retransmitting" processes has a great influence on the focusing property of time reversal waves.

4.2. Effect of vertical deviation of TRA elements

It is expected that the elements of the TRA are vertically shifted from the desired height. Therefore, the effects of the vertical fluctuation of the TRA elements are discussed. Figures 8 and 9 show the results of simulations in which the TRA was vertically deviated by \( \pm 0.5 \) cm, \( \pm 1.0 \) cm, \( \pm 1.5 \) cm, and \( \pm 2.0 \) cm. These figures demonstrate that time reversal waves can converge when the TRA is steadily inclined.
Assuming either one of the “receiving process” or the “retransmitting process” is actually performed in the ocean, and the other is executed by computer simulation, the deviation of the heights of the TRA elements (i.e., the difference between the actual height in the ocean and the virtual height assumed in the simulation) is supposed to affect the focusing property of time reversal waves. Therefore, experiments and simulations were conducted, in which the height of each element was alternately shifted upward and downward during the “receiving process” and each element was shifted to the opposite direction during the “retransmitting process.” Figure 9 is the result and it shows that the focusing property of time reversal waves is destroyed if the fluctuation height is more than half the wavelength.

4.3. Effect of the interval between array elements

In the real ocean-scale simulations mentioned until here, the interval between the TRA elements was 1.5 m, which is half the wavelength of 500 Hz. When the depth of the water was 100 m, the number of elements was 67; this is not a realistic scenario. Therefore, effect of decreasing the number of elements and extending the intervals are investigated.

Simulations were executed under the same conditions as mentioned, except for the intervals between elements. Figure 10 shows the signals received at the focus when the interval is 15m, which is to say, the number of elements is 7. It shows that pulse is received clearly and that time reversal waves maintain their focusing property even if the number of elements is reduced.

4.4. Horizontal TRA

JAMSTEC has several horizontal arrays and if these existent horizontal arrays are utilized by adopting the time reversal wave process, it would be possible to develop a new observation method. Hence, the possibility of generating focused acoustic fields of time reversal waves, using a horizontal array installed on the seabed, was examined. Figure 10 shows the results of a real ocean-scale simulation, in which the time reversal wave signal is transmitted from a 200 m-long horizontal array. It is obvious that the focused acoustic field of time reversal waves can be sufficiently generated even with a horizontal array.

5. Conclusion

This study confirmed that acoustic waves can be made to converge to the focus using time reversal waves. This conclusion was reached through tank experiments whose results qualitatively concur with simulation results. The effects of the TRA configuration were discussed and the following matters were clarified: 1) The focused acoustic field can be generated even with a stationary tilting TRA or a TRA whose elements are steadily, vertically shifted. 2) If such tilting or vertical fluctuation occurs between the “receiving” and “retransmitting” processes, the time reversal waves lose their focusing property. 3) It is possible to converge acoustic waves to the focus even with a horizontal TRA. 4) Even if the number of elements of the TRA is decreased, the desired signal can be received at the focus.

We have studied the effect of noise and sound velocity profile to the time reversal focusing [6]. And we plan to conduct research on the application of time reversal waves in underwater acoustic technologies such as acoustic communication, sonar, and acoustic positioning.

6. References