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Time reversal processing to forward scattering waves of underwater targets

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This paper presents a detection of underwater targets using a time reversal. When a target exists between a sound source and a time reversal array in shallow water, the time reversal array receive sound waves from the sound source and waves scattered by the target. If a time reversal processing to them is carried out and they are re-transmitted from the time reversal array, it will be thought that they are converged at the position of the sound source and the target. However, since the waves converging at the sound source have a high level, the waves converging at the target position are usually masked by the high level sounds. Then, we cannot observe the waves converged at the target. We eliminate only the high level sounds from the sound fields. In each array element, the signals in case of non target are subtracted from the signals including the target. As a result of subtraction, the components of the scattering wave by the target are left on the array elements. The time reversal fields of the scattering wave are constructed by radiating the components of the scattered waves from each element again.

1 Introduction

The researches on time reversal increase it in the field of underwater acoustics [1-9]. The research that processed a time reversal to a reflected wave from an object has recently developed remarkably [10-14]. Especially, the concern for a research related to the DORT method has risen. The time reversal processing is iterated to backscattered waves from the object. The scattered wave converges on a different target. However, an enough scattered wave might not be obtained for a small object and a low frequency. On the other hand, the level of a forward scattering wave is larger in general than the level of the backscattered wave from the small object. We previously proposed a time reversal processing method to forward scattering waves [15]. That is, a pulse and an antiphase pulse are transmitted from a sound source, traveling waves from the sound source are deleted, and the target is detected. Here, the converging field when the multiple targets are present is searched for, and a removal method of an unnecessary image is examined.

2 Phase Conjugation in Shallow Water

2.1 Phase conjugation

A sound source and an array are set up in shallow water as shown in Fig. 1. The sound waves transmitted from the sound source are received at the array allocated from it to a remote point. And, when transmitting from the array again after a phase conjugation processing is executed to the signal, the sound waves at a reception point are shown by the following equation [1],

$$G_{cw}(\mathbf{r},\mathbf{r}_s)=\sum_{n=1}^{N}G_\omega^*(\mathbf{r}_n,\mathbf{r}_s)G_\omega(\mathbf{r},\mathbf{r}_n) \quad , \qquad (1)$$

where $G_\omega(\mathbf{r}_n,\mathbf{r}_s)$ is Green's function concerning propagation from a sound source to an element of a transducer array and $G_\omega(\mathbf{r},\mathbf{r}_n)$ is Green's function concerning propagation from the element to a reception point. $\mathbf{r}$ shows the range, and s, n, and * show the sound source, element number, and complex conjugate, respectively. It is shown in a time domain by the following equation though Eq. (1) is a presentation form in a frequency domain [2],

$$P_{pc}(r,z;t)=\sum_{j=1}^{J}\int G_\omega(r,z,z_j)G_\omega^*(R;z_j,z_{ps}) \times e^{i\omega T}S^*(\omega)e^{-i\omega t}d\omega \quad , \qquad (2)$$

where G_ω, t and z are Green's functions, time, and depth, respectively. R is a horizontal distance from a sound source to an array, and r is a range from an array to a reception point. $S(\omega)$ is frequency spectrum of the sound wave transmitted from the sound source, and ω is an angular frequency. The range of an application of this equation is not specially limited to a sound source though this equation is often used when a convergence property near the sound source of the phase-conjugate wave is examined.

2.2 Sound fields except sound source

The relational expressions shown in the previous section are not the equation limited to the sound source. Then, a phase conjugation to sound field at arbitrary points other than the source location is examined. That is, an arbitrary point is assumed in the middle of a sound source and an array as shown in Fig. 1. The arbitrary point is considered to be a position of a new sound source. A driving signal of the new

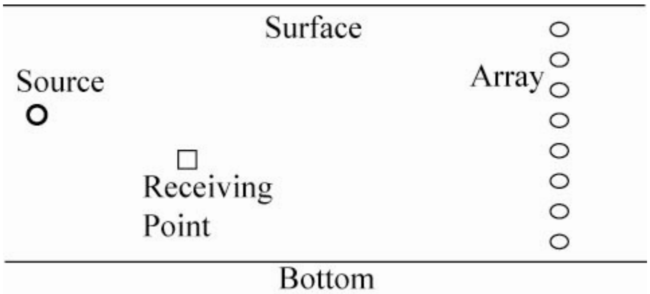

Fig. 1. Arrangement of a source and an array

sound source is supplied from the original sound source. Therefore, a relation between the frequency spectrum of the original sound source and the frequency spectrum of the new sound source is expressed as follows,

$$S_p(\omega) = S(\omega) G_\omega(r_p; z_p, z_s) \quad , \qquad (3)$$

where suffix p means arbitrary point.

Next, a phase conjugation at arbitrary point is examined by using Eq. (2) and Eq. (3). In case of a conventional phase-conjugate wave, a sound pulse transmitted from the sound source is received with the transducer array for the disposition shown in Fig. 1 and a time reversal processing is executed at each element. Afterwards, when the signals are transmitted again from each element, the similar pulse to the transmitted pulse is formed at the source location. Then, it is examined whether the characteristics similar to a conventional phase-conjugate wave is maintained at an arbitrary point. That is, the similarity with a direct wave and a time-reversed signal is examined at the arbitrary point on the middle of the sound source and transducer array.

3 Simulated results

3.1 Comparison between direct wave and time reversal wave at arbitrary point

The depth is set to 100 m in the disposition shown in Fig.1 and the range between the sound source and the transducer array is set to 2.5 km. The sound speed and the density of seawater are 1500 m/s and 1000 kg/m^3, respectively. Those of sediment are 1600 m/s and 1500 kg/m^3, respectively. A tone burst wave of a centre frequency 500 Hz and a pulse width 8 cycles is transmitted from the sound source set up in 50 m in depth. The wave form and spectrum of the tone burst wave are shown in Fig. 2. A wide band pulse is used in the simulation to investigate the waveform of the pulse in detail. These sound pulses are received at the transducer array, and the time reversal processing is executed at each element. And, the time-reversed signals are re-emitted from each element. The re-emitted sound waves are received at the waypoint of the sound source and the transducer array (at the receiving point in Fig. 1). And, a similarity of the phase conjugated signal and the driving signal formed there is examined.

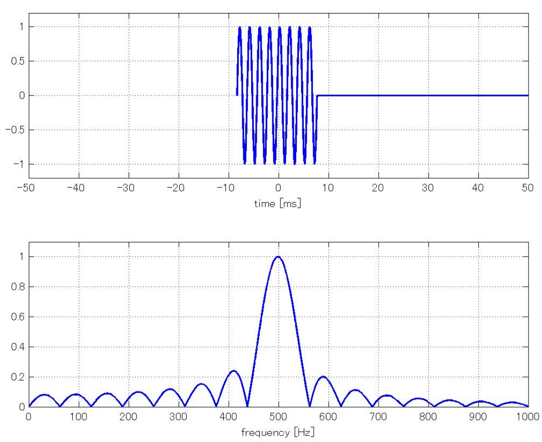

Fig. 2. Wave form and spectrum of transmitted pulse

At a point of the range 1 km from the sound source, the sound wave that enters directly from the sound source is compared with the time reversal wave. In this case, the pulse transmitted from the original sound source is a tone burst wave. The waveform and the frequency spectrum are shown in Fig. 2. The spectrum shown in Fig. 2 corresponds to $S(\omega)$ of Eq. (2). The band width of the frequency spectrum used to calculate is wide-band 350 Hz because it expresses the waveform at an arbitrary point in detail. This bandwidth corresponds to the band width to the third lobe of the frequency spectrum that shows in Fig. 2. On the other hand, the frequency spectrum of the new sound source is easily obtained by the Fourier transform of the sound pulse that enters directly from the original sound source at the position of the new sound source though the frequency spectrum of the new sound source is related to the frequency spectrum of the original sound source by Eq. (3). A position of the new sound source is set to the range 1 km and 50 m in depth. The sound pulse that enters from the original sound source at the position of the new sound source and the waveform of the time reversal wave are shown in Fig. 3. The upper figure is the sound pulse that enters from the original sound source to the position of the new sound source, and the bottom figure is the waveform of the time reversal wave.

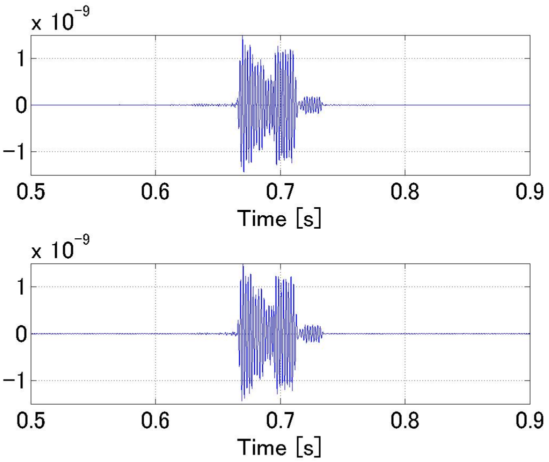

Fig. 3. Pulse forms at range 1 km and depth 50 m. Upper: direct wave, bottom: time reversal wave.

Because the travelling direction of the time reversal wave is opposite to the travelling direction of the direct wave, the time reversal wave is displayed by the reversing time coordinate. Moreover, the frequency spectrum $S_p(\omega)$ shown in Eq. (2) is obtained from the sound source directly by its Fourier transform considering the sound wave that enters at a reception point to be a new sound source.

The waveform of the sound wave that enters directly from the sound source agrees with the waveform of the time reversal wave. It is understood from the above-mentioned result that the phase conjugation is maintained at the arbitrary point between the source and the array.

3.2 Time reversal wave to sound source

A sound source and a transducer array are allocated in shallow water as shown in Fig. 1, and a target is put between those. Water depth is set to 100 m, and the range between the sound source and array are set to 3 km. The target of almost boxy iron is put at range 1.5 km and 50 m in depth. The pulse of a centre frequency 500 Hz is transmitted from the sound source put in 50 m in depth. The transmitted pulse hits the target and the scattered wave is generated. Therefore, traveling waves from the sound source and the scattered waves from the target reach the array almost simultaneously. A time reversal processing is given to those signals, and the reversed signals are transmitted from the array again. Fig. 4 shows the amplitude distribution of sound pulses transmitted again, that is, the time reversal wave (TRW). A coupled modes method is used for the calculation of the sound field [15]. The figure clearly shows that the TRW converges at the position of the original sound source. However, because the level of the traveling wave is larger than the level of the scattered wave, the target is not detected.

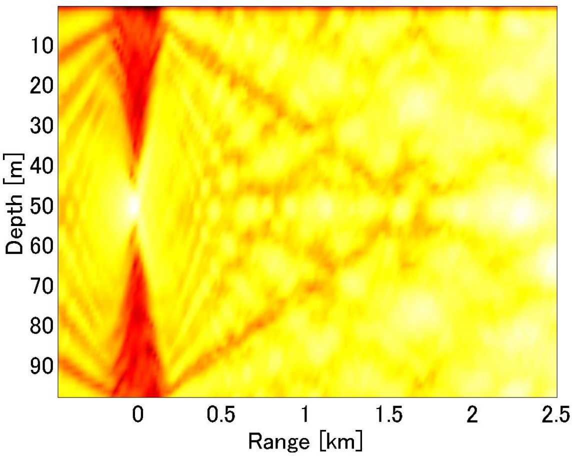

Fig. 4. Amplitude distribution of the time reversal pulse in the case of presence of a target

3.3 Time reversal wave of scattered wave from target

To separate a traveling wave from a source and scattered waves by a target, the traveling wave is deleted using an antiphase pulse. That is, a sound pulse is transmitted when the target is not present beforehand, and the signals received at each element of the array are preserved. Afterwards, the pulse of the antiphase is transmitted when the target is present, and the signal received at each element of the array is preserved. Next, the signal that receives when the target is present, and the signal that receives when the target is not present are added. We previously showed that the TRW of the scattered wave only was formed by transmitting again time-reversing the added signal [16]. Fig. 5 shows the amplitude distribution of the time reversal pulse of the scattered wave from the target. There is little converging to an original source location, and the TRW converges only at the target position. The convergence pattern similar to Fig.5 was shown for the targets put at the range 1 km and 2 km.

From the above-mentioned result, it is clear that the components of the traveling wave are deleted over the wide area between the sound source and the array.

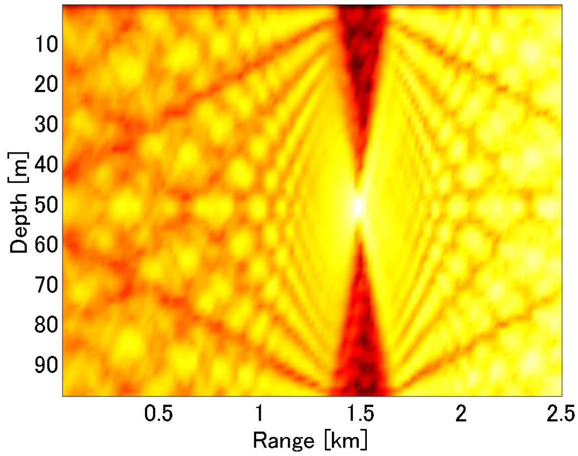

Fig. 5. Amplitude distribution of the time reversal pulse for scattered waves from a target.

3.4 Time reversal waves of scattered wave from vertical array target

When two targets are perpendicularly allocated to the range of 1.5 km, the time reversal wave of those scattered waves is shown in Fig. 6. The depths of the targets are 40 m and 60 m. The individual target is clearly separated. However, a sound field to each target on the way interferes mutually, and a pseudo target is generated. Moreover, the part where the level of amplitude is high is caused in an area near the array. Next, when three targets are perpendicularly allocated at the range of 1.5 km, the time reversal wave of those scattered waves is shown in Fig.7. The depths of the targets are 30, 50, and 70 m.

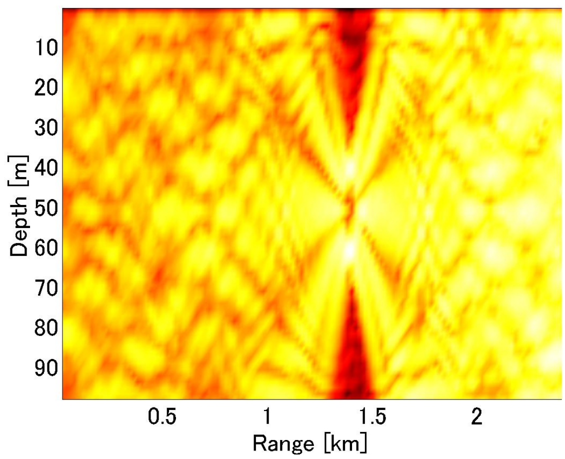

Fig. 6. Amplitude distribution of the time reversal pulse for scattered waves from vertical two targets.

This figure clearly shows three targets. And, an indefinite point with high level doesn't appear. It is thought that this reason originates in the array of the target. Then, the disposition of the target is changed in the following section and the sound field is investigated.

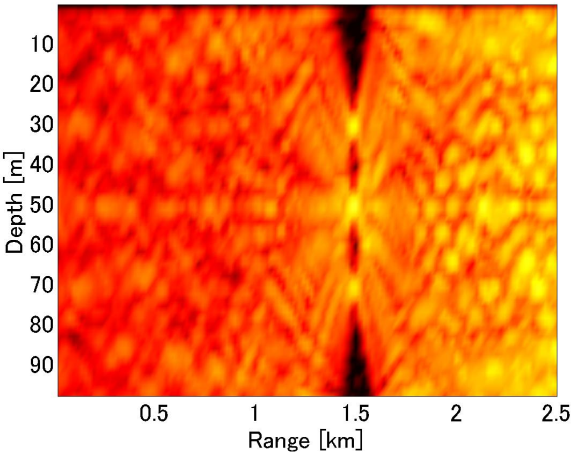

Fig. 7. Amplitude distribution of the time reversal pulse for vertical three targets.

3.5 TRW for target with different range

When two targets are horizontally allocated to the range of 1.5 km and 1.7 km, the time reversal wave of those scattered waves is shown in Fig. 8. The depth of each target is 50 m. The target of the range 1.7 km is not clearly identified though the target of the range 1.5 km is clearly shown. Next, the time reversal wave to the target with a different depth and range is shown in Fig. 9. The range and the depth of the first target are 1.5 km and 50 m. And, those of the second target are 1.6 km and 60 m. The first target is clearly shown as well as the case of Fig.8. The second target is polluted because of masking by the convergence pattern of the first target. In the following section, the reduction of pollution is examined.

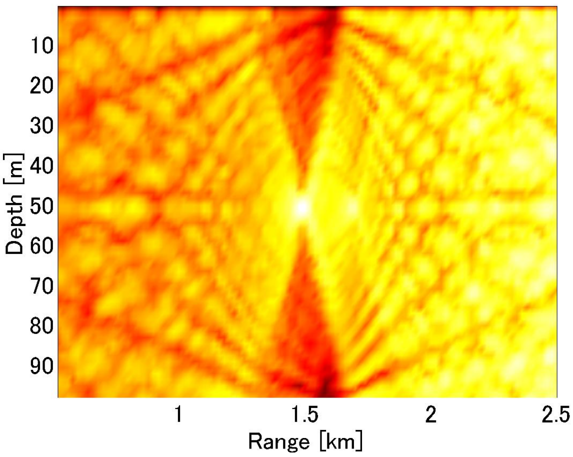

Fig. 8. Amplitude distribution of the time reversal pulse for horizontal two targets.

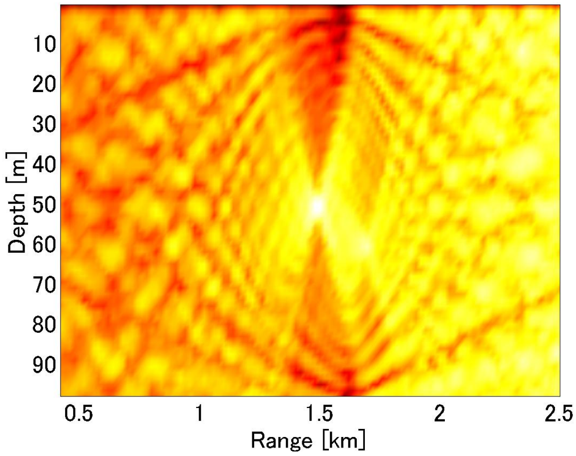

Fig. 9. Amplitude distribution of time reversal pulse for two targets with different depth

3.6 Correlation processing

The image of the second target is covered to the sound pressure distribution that accompanies the convergence pattern of the first target in Fig. 8 and 9..
To delete this unnecessary sound field, the conjugate property of an arbitrary point described in section 3.1 is applied. That is, at the position of the target, the time reversal wave transmitted from the array is similar as shown in Fig. 3 with the pulse that enters directly from the sound source. However, the time reversal wave transmitted from the array is not similar with the pulse that enters directly from the sound source excluding the position of the target.
Then, the correlation of the incident wave and the time reversal wave is taken in field points, and the distribution of the correlation is obtained. The distribution of the correlation of the incident wave and the time reversal wave is shown in Fig. 10 for the target of the disposition similar to Fig. 8. The range from the target to the array has been expanded in this figure. The level of the time reversal wave decreases with the range from the array. Therefore, the amplitude level of the correlation tends to rise in a part near the array. Therefore, because the point with high level is partially caused, the level is corrected in consideration of divergent of the range for the time reversal wave.

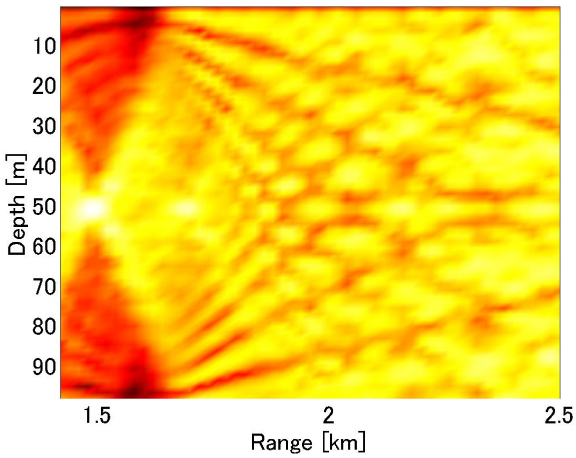

Fig. 10. Correlation between direct pulse and time reversal pulse for horizontal two targets.

As a result, the point with high level that accompanies the convergence pattern disappears, and two targets are identified clearly. The distribution of the correlation of the incident wave and the time reversal wave is shown in Fig. 11 for the target of the disposition similar to Fig. 9.

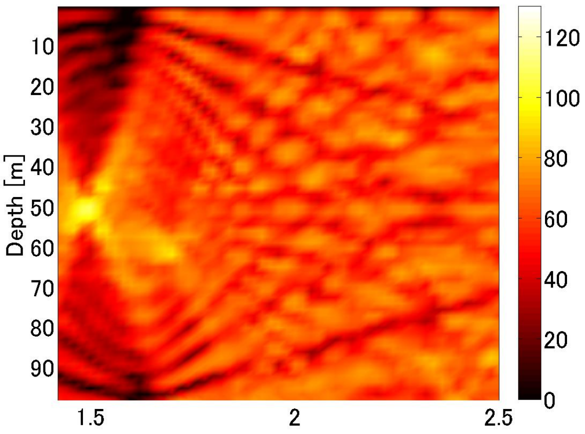

Fig. 11. Correlation between direct pulse and time reversal pulse from source for two targets with different depth..

4 Conclusions

The time reversal was applied to the detection of the multiple target. A forward scattering wave and a direct propagating wave caused by the target were separated, and the sound field of the time reversal wave was obtained. Masking by an unnecessary sound field is caused for the target of planar geometry though the multiple target of a perpendicular array was easily identified. The correlation of the incident wave and the time reversal wave is effective to prevent this pseudosound.

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