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Robust time reversal processing for active detection of a small bottom target in a shallow water waveguide*

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Abstract: With the spatial-temporal focusing of acoustic energy, time reversal processing (TRP) shows the potential application for active target detection in shallow water. To turn the 'potential' into a reality, the TRP based on a model source (MS) instead of a physical probe source (PS) is investigated. For uncertain ocean environments, the robustness of TRP is discussed for the narrowband and broadband signal respectively. The channel transfer function matrix is first constructed in the acoustic perturbation space. Then a steering vector for time reversal transmission is obtained by singular value decomposition (SVD) of the matrix. For verification of the robust TRP, the tank experiments of time reversal transmission focusing and its application for active target detection are undertaken. The experimental results have shown that the robust TRP can effectively detect and locate a small bottom target.

Key words: Robustness, Time reversal processing, Bottom target detection, Uncertain environment, Sonar
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1 Introduction

Time reversal (TR) is a process of retransmitting the signal received from a physical probe source (PS) in a time-reversed order. The time-reversed signal can focus on the position of the PS, and the extended waveform due to the multi-path propagation is compressed. The spatial-temporal focusing ability of time reversal processing (TRP) suggests its potential application to active detection of the weak echo often masked by reverberation from rough ocean boundaries (Kim *et al*., 2004). Here, the word 'potential' means that conventional TRP is dependent on the PS. In practice, it is impossible to place a PS at the vicinity of the target to be detected. The advantage of TRP can be used to improve the echo-to-reverberation ratio in the returning backscattered field, resulting in a performance enhancement of the target detection. Therefore, TRP without a PS has attracted more interest.

At present, for TRP without a physical PS, there are three approaches to focusing acoustic energy on the target. With a virtual PS, the possibility of shifting the focus in range through an implemented frequency shifting procedure was demonstrated in (Song *et al*., 1998; Walker *et al*., 2006; Li *et al*., 2009). Thus, it is not necessary for the PS to be placed at the focus position. Second, a surrogate PS could be obtained using the DORT (decomposition of a time reversal operator) method, which is performed on the echo data from the conventional active transmission (Lingevitch *et al*., 2002; Prada *et al*., 2007). A segment of the echo data is chosen to be time-reversed and transmitted back until the time reversal signal focuses on the target (Song *et al*., 1999). Third, in the process of the time reversal operation, the PS indirectly provides the channel knowledge from the focus position to the time reversal array (TRA) (Ruan and Gong, 2008). Thus, transmission focusing can also be

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achieved by pre-steering the transmitted signal using the channel transfer function, which can be calculated by forward modeling (Li *et al*., 2008; 2009). Correspondingly, many algorithms for robust matched field processing (MFP) can be used.

In the electromagnetic domain, time reversal detection methods are also quickly developed. For a single antenna, time reversal detection methods outperform conventional detection methods, as theoretically approved by Moura and Jin (2007). Also, a 2–4.7 dB gain for the detection of a buried target was obtained using antenna arrays (Jin and Moura, 2009).

Our objective in this paper is to develop a robust TRP without a PS for active target detection. TR transmission focusing with a modeling source (MS) and its robustness are both discussed in Section 2. The combination of robust TRP and a matched filter for active detection is investigated in Section 3. The waveguide tank experimental results of the detection of a small bottom target are shown in Section 4. Section 5 concludes the paper.

2 Robust time reversal processing

2.1 Spatial-temporal focusing with a model source

As previously discussed, the PS indirectly provides the channel transfer function by which the steering vector is obtained for time reversal transmission focusing. If the channel transfer function can be estimated in advance, it is possible to remove the PS. The research on MFP gives a possible method of generating the required channel transfer function using a forward modeling method with the known environmental parameters.

Assume the environmental parameters including water depth, sound profile, and characteristics of the sediment are known. With the MS and the configuration of a TRA, acoustic propagation models can be used to estimate the channel transfer functions. Here, the KRAKEN normal mode model (Porter, 2001) is used to calculate the channel transfer function $\boldsymbol{g}(\omega)$, an $N\times1$ spatial column vector, in which N is the number of transducers of the TRA. Thus, the signal received at the TRA is

$$\boldsymbol{R}(\omega)=\boldsymbol{g}(\omega)S(\omega), \tag{1}$$

where $S(\omega)$ is the signal excited by MS in the frequency domain.

The signal received is reversed in the time domain and the corresponding phase conjugation in the frequency domain. The time reversal signal at the TRA is

$$\boldsymbol{s}(\omega)=\boldsymbol{R}^{*}(\omega)=\boldsymbol{g}(\omega)^{*}S(\omega)^{*}, \tag{2}$$

where $(\cdot)^{*}$ is a complex conjugation. By the acoustic reciprocity, the channel transfer function from TRA to the MS is equivalent to that from the MS to TRA. Therefore, the focusing signal at the MS is

$$\begin{aligned}R_{\mathrm{tf}}(\omega)&=\boldsymbol{s}(\omega)^{\mathrm{T}}\boldsymbol{g}(\omega)=\boldsymbol{R}^{\mathrm{H}}(\omega)\boldsymbol{g}(\omega)\\&=\left(\boldsymbol{g}(\omega)S(\omega)\right)^{\mathrm{H}}\boldsymbol{g}(\omega)\\&=|\boldsymbol{g}(\omega)|^{2}S^{\mathrm{H}}(\omega),\end{aligned} \tag{3}$$

where $(\cdot)^{\mathrm{T}}$ and $(\cdot)^{\mathrm{H}}$ are a vector transpose and a conjugate transpose respectively. The subscript ‘tf’ describes the transmission focusing. Obviously, by Eq. (3), the MS can play the role of the PS in time reversal target detection (Li *et al.*, 2008; 2009).

Ocean environmental parameters are unavailable to be exactly measured, so the robustness of the forward modeling method needs to be considered. In the next sections, the robustness of TRP is discussed for the narrowband and broadband signals respectively, similar to robust MFP (Baggeroer *et al*., 1993).

2.2 Narrowband signals

Without exact environmental information, one approach is to reconstruct the received signal in a form that spans the range of the possible uncertainties. First, a disturbance matrix is constructed using multiple channel transfer function vectors produced by uncertain environment parameters (Kim *et al.*, 2003). Assume the uncertain parameter set is $\boldsymbol{\Theta}=[\boldsymbol{\Phi}-\Delta\boldsymbol{\Phi}, \boldsymbol{\Phi}+\Delta\boldsymbol{\Phi}]$, where $\Delta\boldsymbol{\Phi}$ is the quantity of environmental uncertainties (Li *et al.*, 2008). For uncertain environmental parameters $\boldsymbol{\Phi}_l\in\boldsymbol{\Theta}$ (l=1, 2, …, L), the corresponding channel transfer function vector is $\boldsymbol{g}_l(\omega, \boldsymbol{\Phi}_l)$, where L is the number of uncertain parameter groups. Thus, the channel transfer function matrix is

$$\boldsymbol{G}(\omega,\boldsymbol{\Theta})=\begin{bmatrix}\boldsymbol{g}_1 & \boldsymbol{g}_2 & \cdots & \boldsymbol{g}_L\end{bmatrix}. \tag{4}$$

The next step is to derive the steering vector for robust TR transmission. The design of an efficient constraint space for the steering vector is to select the minimum number of vectors that can best approximate the uncertain space. The dimension reduction can be realized using the singular value decomposition (SVD) of the matrix $\boldsymbol{G}(\omega, \boldsymbol{\Theta})$ with a rank K approximation:

$$\boldsymbol{G}(\omega,\boldsymbol{\Theta}) \approx \boldsymbol{U}\boldsymbol{\Sigma}\boldsymbol{V}^{\dagger}, \tag{5}$$

where $(\cdot)^{\dagger}$ is the Hermitian transpose, $\boldsymbol{U}$ is an $N\times K$ matrix whose columns are left singular vectors, $\boldsymbol{\Sigma}$ is a $K\times K$ matrix whose diagonal elements are the singular values of $\boldsymbol{G}(\omega, \boldsymbol{\Theta})$, and $\boldsymbol{V}$ is an $L\times K$ matrix whose columns are right singular vectors. Thus, the steering vector $\boldsymbol{g}_{\mathrm{r}}$ for robust TR transmission is obtained by a linear combination of the signal vectors:

$$\boldsymbol{g}_{\mathrm{r}}(\omega,\boldsymbol{\Theta}) = \boldsymbol{U}\boldsymbol{q}, \tag{6}$$

where $\boldsymbol{q}$ is a $K\times 1$ vector representing the contributions of each singular vector. The singular values tend to decrease rapidly with the decreasing quantity of environmental uncertainties $\Delta\boldsymbol{\Phi}$ (Li *et al.*, 2008).

Finally, the robust TR transmission is achieved when $\boldsymbol{g}(\omega)$ in Eq. (2) is replaced by $\boldsymbol{g}_{\mathrm{r}}$:

$$\boldsymbol{s}_{\mathrm{r}}(\omega) = \boldsymbol{g}_{\mathrm{r}}(\omega,\boldsymbol{\Theta})^{*} S(\omega)^{*}. \tag{7}$$

Thus Eq. (3) is modified to

$$R_{\mathrm{tf}}(\omega) = |\boldsymbol{g}_{\mathrm{r}}(\omega,\boldsymbol{\Theta})|^{2} S^{\mathrm{H}}(\omega). \tag{8}$$

2.3 Broadband signals

The robust method for narrowband signals needs to be adjusted to broadband time reversal transmission, for $\boldsymbol{G}(\omega, \boldsymbol{\Theta})$ is a 3D matrix consisting of the channel transfer functions at different frequency bins in perturbation space, and it is difficult to perform SVD on the $\boldsymbol{G}(\omega, \boldsymbol{\Theta})$ to generate the required broadband steering vector. However, $\boldsymbol{G}(\omega, \boldsymbol{\Theta})$ can be transformed into $\boldsymbol{G}'(t, \boldsymbol{\Theta})$ by inverse Fourier transformation (IFFT), a perturbation matrix in the time domain, and the required broadband time reversal transmission signal each time can be obtained using the robust method for narrowband signals.

Let $s(\omega_p)$ denote a broadband signal with p (p=1, 2, ..., P) frequency bins, and $\boldsymbol{g}_l^{p}(\omega_p, \boldsymbol{\Phi}_l)$ the channel transfer function corresponding to the frequency ω_p. The time domain signal at the TRA is obtained by

$$\boldsymbol{e}_l^{i}(t_i, \boldsymbol{\Phi}_l) = \mathrm{ifft}\{\boldsymbol{g}_l^{p}(\omega_p, \boldsymbol{\Phi}_l) s(\omega_p),\ p = 1, 2, \cdots, P\}, \\ i = 1,\ 2,\ \cdots,\ M, \tag{9}$$

where $\mathrm{ifft}\{\cdot\}$ denotes the inverse Fourier transformation, and M is the data length.

First, we consider the robust design of the amplitude for the time reversal signal. The amplitude perturbation matrix based on uncertain parameter set $\boldsymbol{\Phi}_l$ is followed by

$$\boldsymbol{A} = \left[\sum_{i=1}^{M} |\boldsymbol{e}_1^{i}| \quad \sum_{i=1}^{M} |\boldsymbol{e}_2^{i}| \quad \cdots \quad \sum_{i=1}^{M} |\boldsymbol{e}_L^{i}|\right], \tag{10}$$

where $\boldsymbol{A}$ is an $N\times L$ matrix. Similarly, the amplitude steering vector of TR transmission signal $\boldsymbol{a}_n$ (n=1, 2, …, N) at the nth element of the TRA is obtained from the eigenvector corresponding to the largest singular value of the SVD of $\boldsymbol{A}$.

Then, the waveform of the time reversal signal is considered. A signal waveform matrix of the nth channel is constructed based on uncertain environment parameter sets, i.e.,

$$\boldsymbol{E}_n = \begin{bmatrix} \boldsymbol{e}_1^{1} & \boldsymbol{e}_2^{1} & \cdots & \boldsymbol{e}_L^{1} \\ \boldsymbol{e}_1^{2} & \boldsymbol{e}_2^{2} & \cdots & \boldsymbol{e}_L^{2} \\ \vdots & \vdots & & \vdots \\ \boldsymbol{e}_1^{M} & \boldsymbol{e}_2^{M} & \cdots & \boldsymbol{e}_L^{M} \end{bmatrix}, \tag{11}$$

where $\boldsymbol{E}_n$ is an $M\times L$ matrix. In the same way, the steering vector $\boldsymbol{w}_n$ for the waveform of each channel can be achieved by the SVD of $\boldsymbol{E}_n$. Therefore, the robust broadband signal in the time domain that will be the time reversal transmitted at the nth element of TRA is

$$\boldsymbol{s}_{\mathrm{r}}^{n} = \boldsymbol{a}_n \boldsymbol{w}_n^{\mathrm{T}}. \tag{12}$$

3 Target detection based on robust time processing

3.1 Transmission focusing via time reversal beamforming

In shallow water, the performance of active detection deteriorates due to the reverberation from rough ocean boundaries. Suppression of reverberation is the important aspect for weak target detection enhancement. The reduction of reverberation by TRP with PS was experimentally demonstrated in (Kim *et al.*, 2004; Li *et al.*, 2008; 2009). As discussed in the previous section, theoretically, TRP with MS can also reduce reverberation by projecting more acoustic energy on the target. When the priori information of the environment is known, the steering vector for TRA is obtained from $\boldsymbol{g}(\omega)^*$ in Eq. (2), and the target is lightened by TR transmission. For uncertain environments, the robust steering vector comes from $\boldsymbol{g}_\mathrm{r}(\omega, \boldsymbol{\Theta})^*$ in Eq. (7) and $\boldsymbol{s}_\mathrm{r}^n$ in Eq. (12) for narrowband and broadband signals respectively.

3.2 Reception focusing and matched filtering

Although the target is lightened by time reversal transmission and the echo is enhanced, the echo-to-reverberation ratio for detection of a small target is still lower. Reception focusing is required at the receivers. When the echo is possibly regarded as a second source from a point target, the numerical TR operation can be performed on the received echo data. Like the previous physical TR operation, the channel transfer function is used for a steering vector to correlate with the received signal, by which the reception waveform is obtained:

$$R_\mathrm{rf}(\omega) = |\boldsymbol{g}(\omega)|^2 (\boldsymbol{g}(\omega) S^\mathrm{H}(\omega))^\mathrm{H} \boldsymbol{g}(\omega) = |\boldsymbol{g}(\omega)|^4 S(\omega), \tag{13}$$

where the subscript 'rf' denotes the reception focusing. When the environmental parameters are uncertain, the $\boldsymbol{g}(\omega)$ in Eq. (13) is replaced by $\boldsymbol{g}_\mathrm{r}(\omega, \boldsymbol{\Theta})$ for the narrowband signal, and $\boldsymbol{s}_\mathrm{r}^n$ for the broadband signal. Finally, the focusing waveform is matched to the MS for target detection and the range of the target is evaluated using the estimated time delay referenced to the time reversal transmission time.

4 Waveguide experiments

In the above sections, the robustness of TRP for active detection is theoretically discussed. Here, it is further investigated with tank experiments.

4.1 Experimental setup

All experiments were performed in a lab waveguide (Fig. 1). The waveguide was a tank, which was 12 m long, 1.22 m wide and 1.4 m deep. The tank bottom was covered with a 22 cm thick sand layer. Four sides of the tank had adhering sound absorption materials. The TRA consisted of a vertical linear array of 32 source/receiver transducers each separated by 0.04 m spanning the water column from 0.04 m to 1.28 m. Each of the 32 channels was individually controlled and amplified during transmission and reception. The sample frequency of the data recording system was 50 kHz. The target was an air-filled, steel cylinder shell 0.51 m long and 0.21 m in diameter. To verify the acoustic field time-reversal focusing, an additional vertical linear array (VLA) of the same configuration as the TRA was used. The geoacoustic parameters required for the numerical calculation of the channel transfer function are also shown in Fig. 1. The bottom sand layer had a density of 1.8 g/cm^3, a sound speed of 1697 m/s, and a sound attenuation of 0.673 dB/km. The water column has a sound speed of 1480 m/s and a density of 1.0 g/cm^3. The media under the sand layer had a density of 1.583 g/cm^3, a sound speed of about 1580 m/s, and a sound attenuation of 0.113 dB/km (Li *et al.*, 2008).

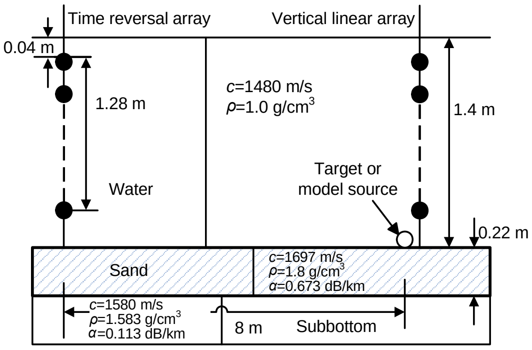

Fig. 1 Time reversal detection experimental setup

4.2 Robust time reversal focusing

For verification of the robust TRP, a 2-ms linear frequency modulation (LFM) pulse with frequency 15–20 Hz broadband signal was chosen for robust TR transmission, and the VLA was placed at the anticipated focus position. The MS was assumed at the tank bottom with a range of 8 m from TRA (Fig. 1). The water depth was assumed to be an uncertain parameter, varying from 1.3 m to 1.5 m. The true water depth was 1.4 m. For comparison purposes, BS (broadside) transmission and TR transmission with a PS were also employed. BS transmission was an excitation of the

TRA with equal amplitudes. As discussed in Section 2, TR transmission was the retransmission of the received signal when the maximal amplitude of the transducer equals that of the BS transmission (each transducer with the same amplitude) (Li *et al*., 2009). Fig. 2 shows the measured time reversal acoustic field. Obviously, three TR transmissions (with a PS, environmental parameters match, and an uncertain water depth) can focus the expected position at the tank bottom. By measuring the acoustic energy at the focus position, for TR transmission with a PS, there was approximately 4.6 dB gain over that of BS transmission. Also a 4.0 dB gain corresponding to robust TR transmission with a matched parameter and a 4.8 dB gain for an uncertain water depth were obtained respectively. The correlation coefficient between the focus signal and the MS was also calculated, 0.93, 0.92, and 0.94 corresponding to three transmission methods respectively. Obviously, the extended waveform of TR signal due to multi-path propagation was effectively compressed. Therefore, results of experiments have further verified the theoretical analysis in Section 2.

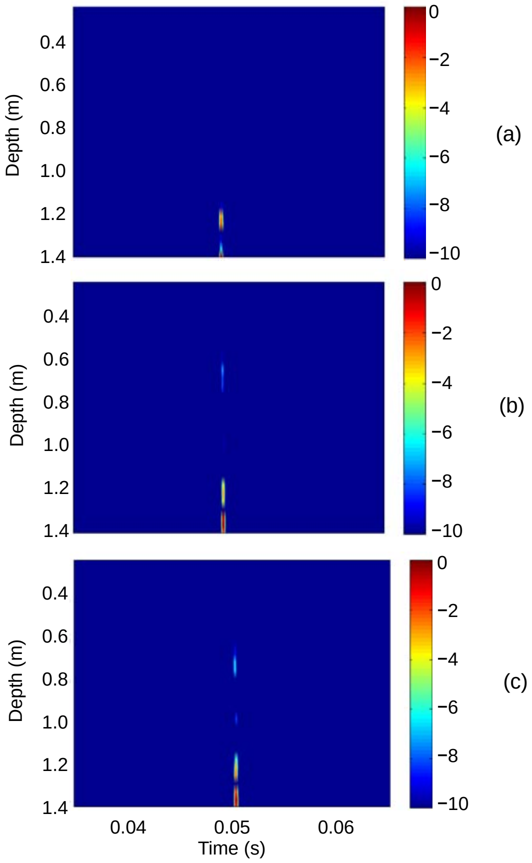

Fig. 2 Normalized energy distribution recorded by the VLA via TR transmission with a broadband signal (2 ms LFM pulse at 15–20 kHz)

(a) TR transmission with a PS; (b) TR transmission with environmental parameters match; (c) Robust TR transmission with an uncertain water depth. The true water is 1.4 m deep. The assumed water depth varies from 1.3 m to 1.5 m

4.3 Detection of bottom target in waveguide tank

Here we investigate the possibility of robust TRP for detection of a bottom target in a tank. The target was placed at the bottom with a distance of 8 m from the TRA. Other experimental conditions were the same as those of the above time reversal focusing experiments.

For evaluation of detection performance, the experiments with TR transmission with a PS and BS transmission were also performed in the tank. For robust TR transmission, the detection performance was investigated for the environmental parameters match and an uncertain water depth respectively. By repeating BS transmission and TR transmission respectively, the echoes were received by the TRA. Then recorded echoes were added coherently, and a matched filter was used for the detection of the target. Correspondingly, the range of the target was estimated according to the time delay referring to the transmission time.

Fig. 3 indicates the results of the TR detection of a small target under three conditions: (1) TR transmission with a PS, (2) TR transmission with environmental parameters match, and (3) robust TR transmission with an uncertain water depth. For TR transmission, the target was clearly detected and the estimated range of the target was near the true position (Figs. 3a–3c). However, the target was not detected for BS transmission in Fig. 3d. With the PS, the channel transfer function used for the TR transmission steering vectors was correctly estimated, and more acoustic energy was projected on the target; thus, the received echo was the strongest, and the match filter output had the largest value, which can be seen from the amplitude of the correlation peak in Fig. 3a. For TR transmission with parameters match and robust TR transmission, almost the same amount of the acoustic energy was projected at the target (Figs. 2b and 2c). Therefore, there were equivalent echo strengths and almost the same detection performance at receivers, which can be seen from a comparison of the amplitudes of Figs. 3b and 3c.

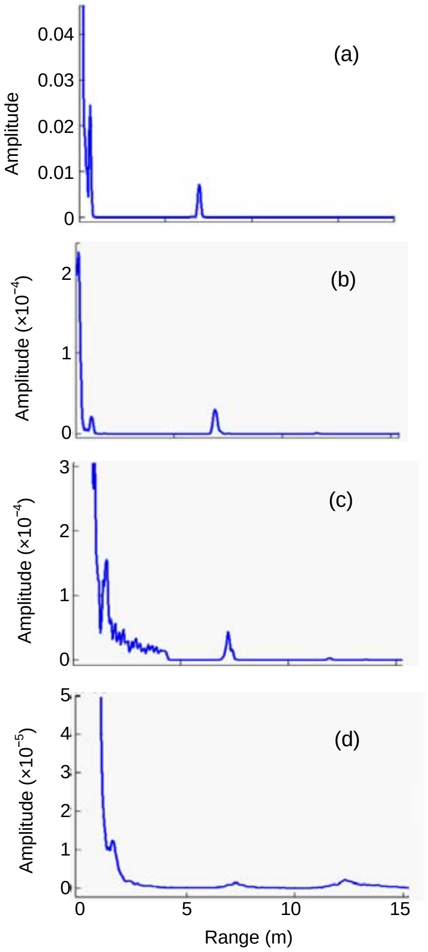

Fig. 3 Detection of a bottom target in waveguide
(a) TR transmission with a PS; (b) TR transmission with environmental parameters match; (c) Robust TR transmission with uncertain water depth (the true water depth is 1.4 m, and the assumed water depth varies from 1.3 m to 1.5 m); (d) BS transmission

5 Conclusion

With the requirement of a probe source at the vicinity of the target, conventional time reversal processing is limited for active target detection. In order to overcome the limitation, this paper investigated the TRP without a probe source replaced by a model source. For uncertain ocean environments, the robustness of TRP is discussed for narrowband and broadband signal respectively. The tank experimental results have shown that the proposed robust TRP can effectively detect and locate the small bottom target.

This paper is aimed to investigate the possibility of time reversal processing for active detection. In practice, more issues have to be addressed, e.g., the robustness of the short array based TRP, the impact of inexact measurements of the sound speed profile, and so on. These are left for future topics.

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