NEW SCHUR-TYPE-BASED PCI ALGORITHMS FOR REVERBERATION SUPPRESSION IN ACTIVE SONAR

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ABSTRACT

This paper presents two fast kinds of principle component inverse (PCI) algorithms using Schur-type subspace estimation methods for reverberation, especially for bottom reverberation suppression in active sonar. These algorithms apply Schur-type method into estimating and deleting the bottom reverberation echoes with a low rank. And the computational structure and complexity of Schur-type method are similar to that of a LQ-decomposition except for the fact that plane and hyperbolic rotations are used. Compared with SVD-based PCI algorithm, these Schur-type-based algorithms have a similar estimation and separation for the reverberation subspace, but are more computationally efficient. In addition, because two Schur-type-based algorithms work column-wise, these are easy to be implemented in real-time parallel DSP system.

1. INTRODUCTION

In shallow water environment, the target detection in the presence of reverberation is a very difficult work in active sonar. Reverberation is caused mainly by the multiple reflections, diffusions or diffractions of the transmitted signal by the surface and bottom interfaces. Since the reverberation is strongly correlated with the signal, some classical methods like matched filtering are inefficient. In order to improve detection, some models of reverberation are used, such as a statistical model considers reverberation as nonstationary colored noise [1]. A pre-whiten approach based this statistical model is used for monochromatic transmitted signals and wide-band signal [2], [3]. However, because this statistical model does not take into account the relation between reverberation and transmitted signal, the pre-whiten procedure is inefficient when target echo and reverberation echo have similar Doppler properties. So another reverberation model which considers the relation between transmitted signal and reverberation is proposed. In [4], a point-scatter model which considers reverberation as a sum of undesirable echoes reflected from many point scatters is used, and a principle component inverse (PCI) algorithm based this point-scatter model is used to estimate and delete the higher reverberation echoes, particularly bottom reverberation before applying the classical detection method. This PCI algorithm makes use of a low rank characteristic of reverberation subspace similar with transmitted signal,and estimate and separate the reverberation subspace via the singular value decomposition (SVD) method. By comparison with the pre-whiten method, the PCI method is effective whatever the respective Doppler. However, it is inefficient in the actual application of active sonar, because the SVD method is computationally expensive and yields more information than necessary to separate reverberation subspace. This is not applicable for real-time processing. Therefore, more efficient "approximate SVD" algorithms have been presented,such as the rank revealing QR factorization, the URV decomposition, and the Schur-type method [5], [6].

In this paper, before the processing of the classical Block Normalized Matched Filter (BNMF), a Schur-type method is applied into the PCI algorithm to estimate and separate reverberation subspace by the spatio-temporal data after the wide-band beamforming. The computational structure and complexity of Schur-type method are similar to that of a LQ-decomposition except for the fact that plane and hyperbolic rotations are used, so it can improve the computational efficiency of PCI algorithm. And Schur-type method's characteristic of processing in column-wise is much fitted for the realization of the real-time parallel DSP system.

As follows, in section **2**, at **2.1**, the PCI algorithm for spatio-temporal data after wide-band beamforming is reviewed [4]; at **2.2**, two kinds of the PCI algorithms used Schur-type method which are low computational cost for estimating reverberation subspace are introduced; and at **2.3**, the choice of threshold γ dealing with PCI processing is discussed. In section **3**, comparing results of the three PCI methods, which are obtained by processing the data from simulation in real bottom reverberation, are presented. Finally, in section **4**, conclusions are given.

2. PROPOSED ALGORITHM

2.1. Description of the PCI Algorithm

The PCI algorithm, which is a particular case of subspace methods, is used to separate reverberation and the target echo by estimating the reverberation subspace [7]. This algorithm models reverberation as a sum of echoes issued from the transmitted signal implies that reverberation and the target have almost the same properties,and assumes that reverberation power is much greater than both signal and white noise power. As a consequence, the reverberation subspace can been obtained and deleted via the SVD. In [4], it has been shown that the PCI algorithm for spatio-temporal data after wide-band beamforming which resolves the rank problem has a better separation for the reverberation subspace. As follows, this algorithm is introduced detailed.

Assume the signal is received by K sensors linear array. The detection problem after time sampling is

$$\begin{cases} H_0 & : \quad x_{t,k} = n_{t,k} + b_{t,k} \\ H_1 & : \quad x_{t,k} = n_{t,k} + b_{t,k} \end{cases}$$

where $x_{t,k}$ is the receive signal on sensor k at time t, and $0 \leq t \leq N_r - 1$ and $1 \leq k \leq K$. The target echo $s_{t,k}$ on sensor k is written as follows:

$$\begin{cases} s_{t,k}(A, \tau_k, f_D) = A\bar{s}_{t,k}(\tau_k, f_D) \\ \bar{s}_{t,k}(\tau_k, f_D) = e_{t-(\tau_k+(l_k sin\theta/c))} exp(2i\pi f_D t) \end{cases}$$

where θ is its direction of arrival, c is the sound speed, τ_k is the delay between the sensor k and a reference sensor, l_k is the distance between the sensor k and the reference sensor. The statistic test of the BNMF is:

$$L(\tau, f_D, \theta) = \frac{(1/2N_r K)^{-1} |\sum_{k=1}^{K} \sum_{t=0}^{N_r-1} \bar{s}^*_{t,k}(\tau, f_D, \theta) x_{t,k}|^2}{\sum_{k=1}^{K} \sum_{t=0}^{N_r-1} |\bar{s}_{t,k}(\tau, f_D, \theta)|^2 \sum_{k=1}^{K} \sum_{t=0}^{N_r-1} |\mathbf{x}_{t,k}|^2}$$

if $MAX_{\tau,f_D,\theta} > \eta$, H_1 is chosen.

For the PCI ,In order to suppress reverberation before BNMF, it is the most important how to estimate and separate reverberation subspace from the spatio-temporal data from K sensors in a line array. The best solution for separation is when the rank of one echo from one direction is equal to one. Wide-band beamforming is one way to obtain this property. through wide-band beamforming, different echoes can be separated by directions. The output of wide-band beamforming can be described:

$$\mathbf{F}_{t,\theta} = \frac{1}{K} \sum_{k=1}^{K} x_{t-l_k*(\sin\theta/c),k}$$

And the PCI observation matrix is written as follow:

$$\mathbf{Y}_i = \{\mathbf{F}_{t,\theta}\}_{i*M+1 \leq t \leq (i+1)*M, 0 \leq \theta \leq \pi} \tag{1}$$

Every column represents the output of the beamforming for an angle θ. $\mathbf{Y}_i$ can be decomposed into two matrices $\mathbf{Y}_i^r$ which spans the reverberation subspace and $\mathbf{Y}_i^o$ which spans the signal plus white noise subspace:

$$\mathbf{Y}_i = \mathbf{Y}_i^r + \mathbf{Y}_i^o$$

As reverberation is assumed to be stronger than the target echo and white noise, Y_i^r is built with the largest singular values of Y_i. and Y_i^r is the best $d-$rank approximation of $\mathbf{Y}_i$ (d is the rank of the reverberation subspace), if:

$$\mathbf{Y}_i = U\Sigma V^H = [U^r|U^o][\begin{matrix} \Sigma^r & 0 \\ 0 & \Sigma^o \end{matrix}][V^r|V^o]^H \tag{2}$$

From this equation, principal subspace, or the reverberation subspace, is given by $Y_i^r = U^r \Sigma^r V^r$. A estimated reverberation vector $F_{t,\theta}^r$ is then collected from Y_i^r. Finally, the BNMF is done on the vector $F_{t,\theta} - F_{t,\theta}^r$. However, it is noticed that only when larger singular values are greater than threshold γ (mentioned in section **2.3**), $F_{t,\theta}^r$ can be created from $\mathbf{Y}_i^r$.

2.2. Description of the Schur-type method

In section **2.1**, it is shown that the chief problem of PCI algorithm is the problem of low-rank matrix approximation, but SVD is not a fast and efficient method. So some more fast and efficient methods need to be applied for subspace estimation in PCI algorithm. The Schur-type method is just this kind of approach [6]. From equation (2), if the SVD of $Y_i \in R^{M\times n}$ is given by $Y_i = U\Sigma V$,an eigenvalue decomposition (EVD) of its Gramian $G = YY^H$ equals $G = U\Sigma^2 U^H$. If the threshold γ, which contacts with the level of target and white noises, is known, it is easy to show that a spectral shift of the Gramian G by $\gamma^2 I_M$ yields:

$$\gamma^2 I_M - G = U(\gamma^2 I_M - \Sigma^2)U^H$$

therefore, its matrix sign function equals:

$$sign(\gamma^2 I_M - G) = U[\begin{matrix} I_{M-d} & \\ & -I_d \end{matrix}]U^H \tag{3}$$

Where the column space of (3) corresponding to the negative eigenvalues of $\gamma^2 I_M - G$ represents an estimate of the signal subspace.Assume that J is the signature matrix and Θ is $J-$unitary if it satisfies $J = \Theta J \Theta^H$. Therefore:

$$\Theta = [\begin{matrix} \Theta_{11} & \Theta_{12} \\ \Theta_{21} & \Theta_{22} \end{matrix}], \ J = [\begin{matrix} I_M & \\ & -I_n \end{matrix}]$$

the "shifted Gramian" can be expressed as:

$$\begin{aligned} \gamma^2 I_M - G &= [\gamma I_M \quad Y]J[\gamma I_M \quad Y]^H \\ &= [\gamma I_M \quad Y]\Theta J \Theta^H [\gamma I_M \quad Y]^H \\ &= [C \quad D]J[C \quad D]^H \\ &= CC^H - DD^H \end{aligned} \tag{4}$$

where $[C \;\; D] = [\gamma I_M \;\; Y]\Theta$.

$$[\gamma \overset{+}{I_M} \quad \overset{-}{Y}]\tilde{\Theta} = [\overset{+/-}{L} \quad \overset{+/-}{0}] = [\overset{+}{C} \quad \overset{-}{D}]P \tag{5}$$

where $C = [C' \quad 0]$, $C = [D' \quad 0], \tilde{\Theta} = \Theta P$, and L is a lower triangular $M \times M$ matrix. P is a permutation matrix sorting the columns according to their signature, such that C and D contain the column of $[L \quad 0]$ with positive and negative signature, respectively. Equation (5) can be viewed as a 'hyperbolic QR factorization'. the computation of this factorization can be interpreted as a generalized Schur method,which is specifically described in [5], [8]. Thus, a particularly simple reverberation subspace estimation is obtain by the computation of HQR factorization,as follow:

$$Y^r_{S1} = D' \tag{6}$$

where (6) is called as the Schur subspace estimate-1 (SSE-1). This estimation gives quite good results when target echo is outside reverberation. In addition, another improve reverberation subspace estimation is represented:

$$Y^r_{S2} = D' - C'(\Theta^{-1}_{11}\Theta_{12})_{11} \tag{7}$$

where $(\Theta^{-1}_{11}\Theta_{12})_{11}$ denotes the leading $(M-1) \times 1$ block of $\Theta^{-1}_{11}\Theta_{12}$. this estimate,which is called as the Schur subspace estimate-2 (SSE-2), should be used in more critical situations,i.e.,when target echo is inside reverberation.

Because the 2-norm approximations corresponding to Y^r_{S1} and Y^r_{S2} do not necessarily minimize the norm difference, this leads to some performance degradation compared to the "optimal" SVD. However, From simulation results in section 3, this degradation is not obviously. It is because the assumption of PCI algorithm is working in the high reverberation to signal and noise ratio (RSNR). It guarantees that the Schur-type method can obtain good subspace estimation and separation.

2.3. Choosing the Threshold γ

The choice of threshold γ is very important for proposed methods. Through the threshold γ, the PCI algorithm can determine the existence of proposed reverberation subspace and the rank of deleting reverberation subspace. PCI algorithm assumes the reverberation power is much greater than both signal and white noise power, so threshold γ is linked to our prior knowledge of the target and white noise power. Supposing with the variance of the white noise and signal is σ^2, the threshold γ can be given as follow [6]:

$$\gamma > \sigma\sqrt{2N_r} \tag{8}$$

3. SIMULATION RESULTS

In order to compare the two PCI algorithms based the SSE-1 and SSE-2 with the PCI algorithm based SVD subspace estimation, we assume that a linear array of 64 $\lambda/2$-spaced omnidirectional sensors receives some data blocks which consist of the simulated target echo, real bottom reverberation and ambient noise in sea trials. The RSNR is chosen at 20 dB in every receiving sensor and the target echo inside the bottom reverberation.

Table 1. Block calculating time of PCIs (ms)

block size	SVD PCI	SSE-1 PCI	SSE-2 PCI
40×40	4.23	2.41	3.17
80×80	34.31	13.78	18.61
160×160	286.02	95.76	115.93

We consider the blocked observation matrix Y_i (those are 80×80 matrices) after wide-band beamforming. The performance of three methods are compared by the azimuth-range figures after the classical BNMF. Fig.1 and Fig.2 show these results and the target is marked by a white circle. The Fig.1shows the BNMF result without PCI, we notice that lots of false alarm peaks appear and the target almost disappear in this figure. It is because the bottom reverberation has higher power and is highly correlated with the transmitted signal. In this case, target detection is impossible.the Fig.2(a)-(c) show the BNMF result with PCI based the three subspace estimation methods (b is the SVD-based PCI , c is the SSE-1-based PCI and d is the SSE-2-based PCI). It is noticed that false alarm peaks reduce clearly and the target is enhanced obviously after PCI. Meanwhile, comparing with the Fig.2(a)-(c), the three methods have similar performance in suppressing bottom reverberation and SSE-2 estimation looks like removing more false alarm peaks than the others. In addition, we compare the computational efficiency of these methods with the meaning time calculated from quantities of different sizes matrix blocks as Table.1 shown. The results processed by the programmes of standard C applied in DSP show the more efficient algorithm is the SSE-1-based PCI, which time is at about one-third of the SVD-based PCI's. And the SSE-2-based PCI spends more time on processing than the SSE-1-based PCI, but it less than the SVD-based PCI. Moreover, the SSE-based PCIs are more efficient for the large-size matrix blocks.

4. CONCLUSION

In this paper, a quick subspace separation and estimation method named the Schur-type method is used to resolve the problem of suppressing reverberation. From the simulation results, it is shown that two kinds of the Schur-type-based PCI methods have similar effect for estimating and deleting the high bottom reverberation comparing to the SVD-based PCI. However, these Schur-type method is more computational efficiency and is relatively easy to be implemented in real-time parallel DSP system (e.g. ADSP 21060 system).

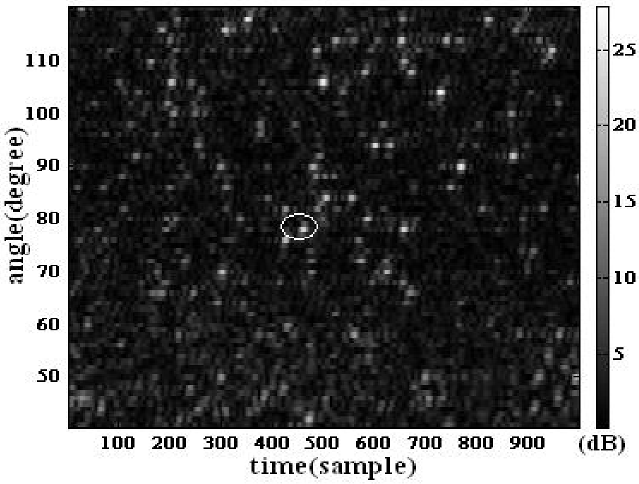

Fig. 1. the BNMF result without PCI.

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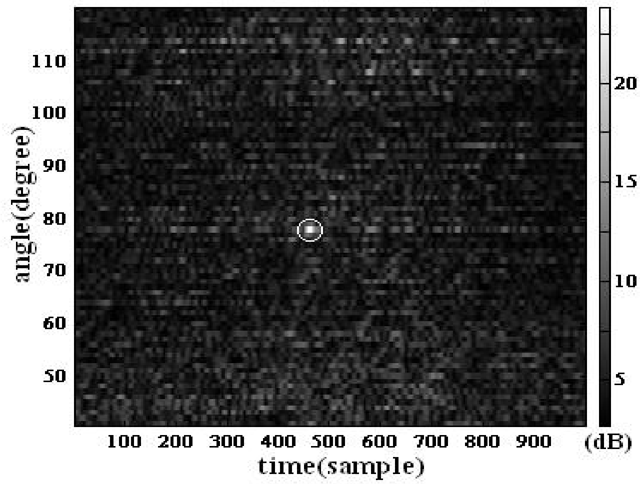
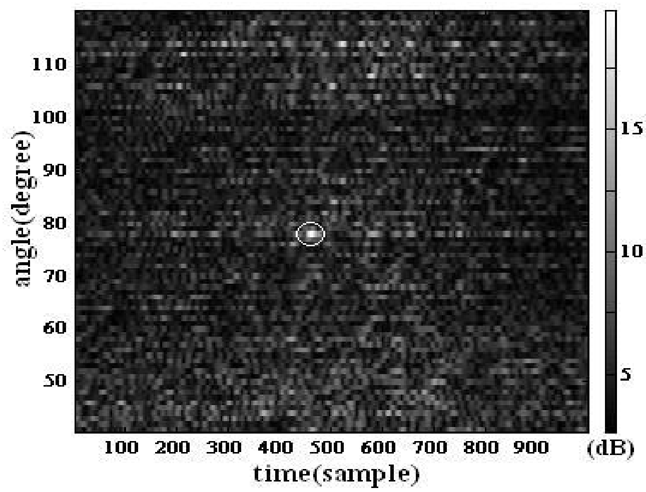


(a)



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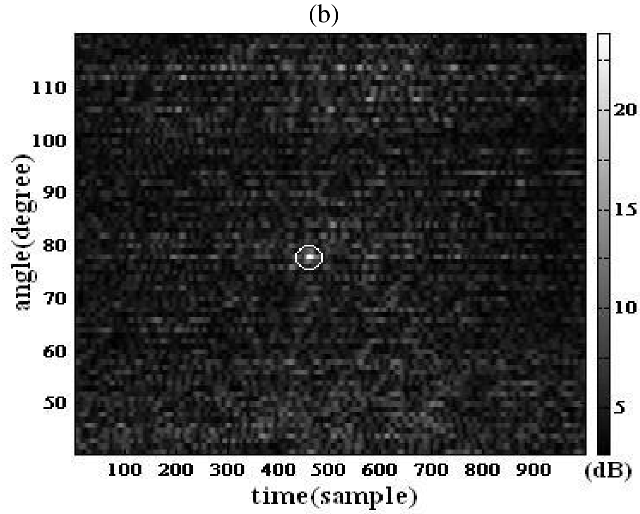

(c)

Fig. 2. the BNMF result with (a) SVD-based PCI, (b) SSE-1-based PCI, (c) SSE-2-based PCI.