The Blind Identification of Multi-Inputs and Multi-Outputs Shallow-Water Acoustic Channel

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Abstract. Blind channel identification/estimation is very important for object detection, trace, localization in the ocean acoustics. Time domain blind identification algorithm requiring exact length of the channel being identification. Due to the characteristics of the shallow-water channel, the length of channel impulse response sequence is uncertain, Hence a frequency domain method for the blind MIMO (Multiple-Input Multiple-Output) underwater identification based on higher order statistics (HOS) is used to estimate the original acoustic channel from received signals on hydrophones only, with the low signal to noise ratio (SNR). The simulation results in the acoustic environment proved this work is effective and efficient for blind identification of the shallow-water acoustic channel.

1. Introduction

Channel estimation is an attractive problem in the application fields of sonar, radar, communications, control, geophysics, etc [1]. The goal of MIMO system identification is to identify an unknown system by multiple input signals and receive signals. In a number of cases, however, as in shallow-water acoustic channel response evaluation from recorded data, the input signal is not readily available or the information is not sufficiently accurate. This problem is often referred to the literature as blind identification since the input and system is inaccessible, and has been extensively studied recently. Most of the existing approaches for MIMO system blind identification operate in the time domain requiring exact length of the channel being identification, and their complexity increases rapidly with channel length, Whereas, frequency domain method needn’t know it exactly in advance. Chen [2] proposed a frequency domain method for the MIMO system blind identification, uses second and higher order statistics of the system output, and applies to the case of white inputs. Inspired by this method, this work considers the underwater channel estimation problem in the frequency domain, and as such, does not suffer from the aforementioned problems.

The shallow-water channel is characterized by strong signal degradation caused by multipath propagation with high spatial and temporal variability of the channel conditions. The HOS is good at the dealing with the non-gauess stochastic process and identifying the non-minimum phase system. This paper aims to employ the HOS based blind identification methodology [2] to address this type of problems for the impulse response estimation of the MIMO shallow-water channel to obtain the estimates of the IR representative of the medium or the emitted signal. The received signal will be
modeled as a weighted sum of time-delayed replicas of the emitted signal. The experiment in section IV indicates that the methodology yields a promising tool in underwater acoustic channel estimation.

2. System model of underwater acoustics channel

Let’s consider an underwater scenario, shown in figure 1, in which two source is positioned at range 0 and depth \(z_0\) and \(z_1\), and a hydrophone receiver is positioned at range \(r_0\) and depths \(z_l\). In a practical application, it is assumed that the hydrophone is a basic component in the complex receiving system. At time instance \(\tau_0\), the source starts to emit an acoustic signal propagating in the medium defined by the ocean with its physical limits. Upon emission by the source, an acoustic field is created, which is partially received by the hydrophone array, after propagation. The field can be represented by the acoustic pressure, which depends on three independent variables (range \(r\), depth \(z\) and time \(t\)), and satisfies the wave equation [3]. The created field is dependent on the source signal and the medium characteristics. All these effects emerge mainly as a consequence of the boundary conditions (water surface, water-sediment interface, geologic strata) and the variations in sound-speed profile throughout the depth (as shown in figure 1).

![Figure 1. The 2i2o shallow-water acoustic channels.](image)

Ray tracing model [4] will be adopted in this paper to describe sound propagation in the sea. The received signal in a hydrophone is described as the sum of the eigenrays’ arrivals. In other words, it is to model the received signal as a sum of weighted and delayed \(M_{ij}\) source signal replicas. Correspondingly, the channel response from \(i\)th source to \(j\)th receiver signal becomes:

\[
h_{ij} = \sum_{m=1}^{M_{ij}} a_m \delta(t - \tau_m),
\]

(1)

The amplitudes and time-delays of \(h_{ij}\) can be grouped into 2 vectors, respectively:

\[
a_{ij} = \begin{bmatrix} a_1, a_2, \ldots, a_{M_{ij}} \end{bmatrix}^T, \quad \tau_{ij} = \begin{bmatrix} \tau_1, \tau_2, \ldots, \tau_{M_{ij}} \end{bmatrix}^T.
\]

(2)

A good approximation to the problem solution can be obtained by regarding the ocean as a filter, with a given IR \(h_{ij} = \{h_{ij}(0), h_{ij}(1), \ldots, h_{ij}(L)\}\); the emitted signal \(s_j(t)\) is convolved with LTI single-channel systems \(h_{ij}\), giving rise to received signal \(x_j(t)\) with additive noise \(n_j(t)\). Let \(h\) represent the impulse response matrix whose \((i,j)\) element is denoted by \(h_{ij}\), \(L\) is the length of the longest \(h_{ij}\), \(x(k)\) is the received signal vector composed of element \(x_j(t)(j=1,\ldots,n)\). \(s(t)\) is the source signal vector, whose element is \(s_j(t)(j=1,\ldots,n)\), the MIMO underwater channel output is

\[
x(t) = \sum_{l=0}^{L} h(l) s(t-l) + n(t)
\]

(3)

The noise \(n(t)\) in the hydrophone is assumed temporally white, zero-mean and uncorrelated with the signal. Source \(s_j(t)\) is a zero-mean, non-Gaussian, nonsymmetrical distributed, independent identically distribution, and has unit variance.
3. Frequency-domain blind Identification algorithm

Here we want to estimate the frequency domain underwater channel matrix $H(\omega)$. And the estimation should satisfy the form:

$$\hat{H}(\omega) = H(\omega) \mathbf{p} \Delta e^{-j\omega \mathbf{D}}$$  (4)

- $\mathbf{p}$ is column permutation matrix. $\Delta$ is constant diagonal matrix. $\mathbf{D}$ is diagonal matrix with integer elements $[2]$.

The cross-correlation matrix of signal vector $x(k)$ is

$$R_X(\tau) = E\left\{x^*(k)x^T(k+\tau)\right\}$$  (5)

Superscripts $^*$ and $^T$ denote complex conjugate and transpose respectively. The cross power spectrum of the received signals is

$$P_X(\omega) = H^*(\omega)H^T(\omega) + E\left\{n^*(\omega)n^T(\omega)\right\}$$

$$= H^*(\omega)H^T(\omega) + \sigma_n^2 \mathbf{I}$$  (6)

A complex prewhitening matrix $\nu(\omega)(m \times m)$ can be found by the prewhitening operation $[5]$

$$\nu(\omega)P_X(\omega) - \sigma_n^2 \mathbf{I}\nu(\omega)^H = \mathbf{I}$$

The cross cumulant of the received signals $x_l(k), x_i^*(k), x_j(k)$ is

$$C_{lilj}(\tau, \rho) = \text{Cum}[x_l(k), x_i^*(k+\tau), x_j(k+\rho)] = \sum_{p=1}^{m} \sum_{q=1}^{n-1} h_{lp}(q)h_{lp}^*(q+\tau)h_{jp}^*(q+\rho)$$  (8)

where $r_{p}^{(3)}$ is the skewness of input $s_p(k)$

$$\gamma_{s_p}^{(3)} = \text{Cum}[s_p(k), s_p^*(k), s_p(k)]$$  (9)

The cross-bispectrum of $x_l(k), x_i^*(k), x_j(k)$ is defined as the two-dimension discrete Fourier transform of $c_{lilj}^{(3)}(\tau, \rho)$, equals

$$C_{lilj}^{(3)}(\omega_1, \omega_2) = \sum_{p=1}^{m} \gamma_{s_p}^{(3)} \mathbf{H}_{lp}(-\omega_1) \mathbf{H}_{jp}^*(-\omega_1) \mathbf{H}_{jp}(\omega_2)$$  (10)

and matrix

$$\mathbf{C}_l^{(3)}(\omega, \theta - \omega) = \mathbf{H}^*(-\omega)$$

$$\begin{bmatrix}
\gamma_{s_1}^{(3)} \mathbf{H}_{l1}(-\theta) & 0 & \cdots & 0 \\
0 & \gamma_{s_2}^{(3)} \mathbf{H}_{l2}(-\theta) & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & \gamma_{s_m}^{(3)} \mathbf{H}_{lm}(-\theta)
\end{bmatrix} \cdot \mathbf{H}^T(\theta - \omega)$$  (11)

and

$$\mathbf{Y}_l^{(3)}(\omega, \theta - \omega) = \mathbf{V}(\omega)\mathbf{C}_l^{(3)}(\omega, \theta - \omega)\mathbf{V}(\theta - \omega)^H$$  (12)

Combining (7) and (11), we get

$$\mathbf{Y}_l^{(3)}(\omega, \theta - \omega) = \mathbf{W}(-\omega)$$

$$\begin{bmatrix}
\gamma_{s_1}^{(3)} \mathbf{H}_{l1}(-\theta) & 0 & \cdots & 0 \\
0 & \gamma_{s_2}^{(3)} \mathbf{H}_{l2}(-\theta) & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & \gamma_{s_m}^{(3)} \mathbf{H}_{lm}(-\theta)
\end{bmatrix} \cdot \mathbf{W}(\theta - \omega)^H$$  (13)

where

$$\mathbf{W}(\omega) = \mathbf{V}(\omega)\mathbf{H}(\omega)^*$$  (14)

From (7) we can see that $\mathbf{W}(\omega)$ is an orthonormal matrix, i.e.,

$$\mathbf{W}(\omega)\mathbf{W}(\omega)^H = \mathbf{I}$$  (15)

The matrix $\mathbf{M}_{\omega}$ is defined as
The Joint Diagonalization \[6\] can be applied to matrix \(M_{IJ}\), the estimation of the matrix \(W(\omega)\) can be obtained
\[
\hat{W}(\omega) = W(\omega)e^{-jM}
\]
From (14), and resolving the phase ambiguous, the solution of estimated \(H(\omega)\) is as follows:
\[
\tilde{H}(\omega) \approx \left[ V(\omega)^{-1} \hat{W}(\omega) \right]^* = H(\omega)Pe^{-jM}
\]
It satisfied with the form of identification result.

The correlation coefficient between the estimation channel \(h^l(n)\) \((l=1,2,...,M)\) and the original channel \(h(n)\) \((n=1,2,...,N)\) is the performance index for the blind identification result of underwater channel.

\[
\rho = \frac{\left| E[h_l^* h_n] \right|^2}{\sqrt{E[h_i^2] E[h_n^2]}}
\]

The average result of all channel correlation coefficient is the MIMO blind identification performance index.

4. The simulation experiment
The blind identification methodology described in the previous section is applied to synthetic shallow-water acoustic data for underwater channel estimation. The environment of underwater channel is shown as figure 1. The synthetic data set corresponds to a canonical two-layered shallow-water waveguide with 135-m water column superimposed to a sediment bottom with the corresponding sound speed profile.

The two acoustic sources are positioned at 90-m and 95-m depth, and two receivers are all located at 5.6-km range, but at different depth of 115-m and 95-m, as illustrated in figure 1. Two source are zero mean random signals and statistically independent each other. The receivers are added with independent white noise of zero mean.

Figure 3 presents the original 2i2o acoustic channel IR computed by BELLHOP ray propagation model as true 2i2o channel responses, and their channel estimate reconstructed by means of the frequency domain blind identification algorithm, they are the mean results of two hundred times identification. The mean correlation coefficient with true channels is 0.9814. The simulation results proved the feasibility of underwater MIMO frequency domain blind identification algorithm.
5. Conclusion
From the simulation result, we can see that the method of frequency domain blind identification does not need the exact length of channel in advance and adapts to the blind estimation of underwater channel. But the computation of HOS is an obstacle of the high speed of blind identification. The average result of the repeated times estimation could be adopted to improve more high precision of the estimation, thus got the channels estimation more correctly.

Their time-delays are proper, but amplitudes have some deviates with true channels. Correct time-delay estimation results are sufficient for object location. HOS method is quicker but due to its computational complexity, is more perplexing than time-domain methods, thus more efficient methods should be developed in the future.

Figure 3. The true 2i2o channel IR and correspond estimation channel.

References
[1] Giannakis G.B and Mendel J.M 1989 IEEE Trans. Acoustics Speech Signal Processing 37 360
[2] Chen B N and Petropulu A.P 2001 IEEE Trans. Signal Processing 49 1677
[3] LI R Y, MA Y L, YANG K D and Zou S X 2004 Proc. the 5th World Congress on Intelligent Control and Automation (Hangzhou vol 4 Piscataway:NJ IEEE Inc.) 3269
[4] Porter M.B 1991 The KRAKEN normal mode program (SACLANT Undersea Research Centre La Spezia Saclantcen Memorandum SM-245)
[5] Douglas S.C 2000 Proc. IEEE Workshop on Independent Component Analysis and Signal Separation (Helsinki vol 1 Piscataway:NJ IEEE Inc.) 579
[6] Cardoso J.-F 1994 Perturbation of Joint Diagonalizers Technical Report Ref# 94d027 (Telecom Paris, France) 2