Signal Processing 88 (2008) 2492–2499

Contents lists available at ScienceDirect

Signal Processing

journal homepage: www.elsevier.com/locate/sigpro

Two-dimensional direction finding of acoustic sources by a vector sensor array using the propagator method

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ARTICLE INFO

Article history:
Received 21 May 2007
Received in revised form 16 April 2008
Accepted 22 April 2008
Available online 4 May 2008

Keywords:
Array signal processing
Direction finding
Multipath
Coherent signals
Acoustic vector sensor
Propagator method

ABSTRACT

This paper considers a new azimuth-elevation direction finding algorithm for multiple acoustic plane wave signals using acoustic vector array. Firstly, a planar-plus-an-isolated sensor array geometry [P. Li, J. Sun, B. Yu, Two-dimensional spatial spectrum estimation of coherent signals without spatial smoothing and eigendecomposition, IEE Proc.-Radar Sonar Navigat. 143(5) (October 1996) 295–299] is exploited and a cross-covariance matrix is defined. Then the propagator method is used to estimate the steering vectors of acoustic vector sensors. Finally, a closed-form, automatically paired azimuth-elevation angle estimates are derived. The presented algorithm shows high azimuth-elevation estimation accuracy due to array aperture extension. In addition, the new algorithm does not need the eigen-decomposition and 2D iterative searching, and is applicable to coherent (fully correlated) signals and spatially correlated noises. Therefore, the algorithm shows low computational complexity and robustness. Monte-Carlo simulations are presented to verify the effectiveness of the proposed algorithm.

1. Introduction

Two-dimensional (2D) direction finding of multiple sources using sensor array techniques has played a fundamental role in some applications involving electromagnetic, acoustic, and seismic sensing. In the past decades, a lot of studies have been conducted on the pressure-sensor array. However, it is found recently that the vector sensor array, without increasing the array aperture, affords more accurate 2D direction estimates.

Acoustic vector sensor model was first introduced into the signal processing community in [3]. Since then, many advanced pressure-sensor array techniques were adapted to the acoustic vector sensor array [1–14]. These techniques have advantages of relative computational simplicity and comparable estimation accuracy at moderate or high signal-to-noise ratio (SNR). However, most of them assume incoherent signals and spatially white additive noises. These assumptions are often violated in many practical situations. The coherent signals and spatially correlated noises [17,18] could critically degrade the performance of the array processing algorithms.

In this paper, we aim to develop a robust 2D direction finding algorithm for coherent acoustic signals in the spatially correlated noises.[1] We firstly define a full rank cross covariance matrix based on the planar-plus-an-isolated sensor array geometry [38]. Then we utilize the so-called propagator method[2] to obtain closed-form

[1] Note that, there exists a variant of algorithms to handle coherent signals and spatially correlated noises using conventional pressure-sensor array. For coherent signals, the spatial smoothing technique and its variants [19–22] have been widely investigated. For spatially correlated noise, we refer to [23–35] for references. Obviously, these techniques could be readily combined and extended for acoustic vector sensors.

[2] The 'propagator' was first defined in [36]. The propagator method offers estimation accuracy comparable to that of its subspace-based counterparts, but requires a much reduced computational complexity.

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doi:10.1016/j.sigpro.2008.04.010

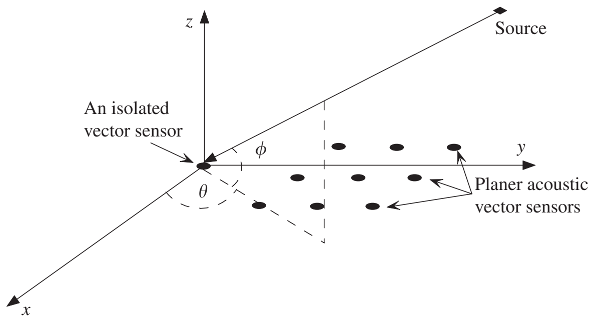

Fig. 1. Acoustic vector sensor array geometry.

automatically paired azimuth-elevation angle estimates. In fact, the propagator algorithm [36] has been used to the array geometry consisting of the pressure sensors [38]. The pressure-sensor array propagator algorithm requires more costly 2D iteratively searching and may suffer DOA cyclical ambiguity when the uniform inter-sensor spacing extends beyond a half-wavelength in accordance with the spatial Nyquist sampling theorem. The proposed algorithm eliminates the above two problems without any additive computational loads. The inherent structure of acoustic vector sensor also allows the array aperture extension to offer enhanced DOA estimation precision.

The rest of this paper is organized as follows. Section 2 formulates the mathematical data model of acoustic vector sensor array. Section 3 develops the proposed algorithm. Section 4 presents the simulation results to verify the efficacy of the proposed algorithm. Section 5 concludes the paper.

2. Acoustic vector sensor array data model

Assume that K narrowband acoustic planer wave source signals, parameterized by $\{\theta_1, \phi_1\}$, $\{\theta_2, \phi_2\}, \ldots, \{\theta_K, \phi_K\}$, impinge upon an acoustic vector sensor array, as shown in Fig. 1. The array consists of a planner vector sensor array and an isolated vector sensor [38]. The planar vector sensor array has L $(L>K)$ identical linear rows of $P(P>K)$ vector sensors each. The rows are parallel and uniformly spaced, and the sensors within each row also have uniform spacing. Each vector sensor has four components, i.e., three velocity sensors and a pressure sensor, co-located in space. The acoustic vector sensor's 4×1 manifold with regard to the kth signal is defined by [3,4,6]

$$\mathbf{c}(\theta_k, \phi_k) \overset{\text{def}}{=} \begin{bmatrix} 1 \\ u(\theta_k, \phi_k) \\ v(\theta_k, \phi_k) \\ w(\phi_k) \end{bmatrix} = \begin{bmatrix} 1 \\ \cos\theta_k \cos\phi_k \\ \sin\theta_k \cos\phi_k \\ \sin\phi_k \end{bmatrix} \quad (1)$$

where $-\pi/2 \leqslant \phi_k < \pi/2$ denotes the kth signal's elevation angle, and $0 \leqslant \theta_k < 2\pi$ represents the kth signal's azimuth angle. The first component of (1), corresponding to the pressure sensor, has function to distinguish between acoustic compressions and dilation. The second to the last components of (1) correspond to the velocity sensor aligned along the x-axis, the y-axis, and the z-axis, respectively. Note that, the acoustic vector sensor array manifold contains no time-delay phase factor. That is, the acoustic vector sensor array manifold is independent of the impinging signals' frequency spectra [8]. This fact is pivotal to improve the estimation accuracy by array aperture extension beyond spatial Nyquist sampling theorem.

Without any loss of generality, we further assume the isolated acoustic vector sensor be deployed at the origin. With a total of K source signals, the entire 4×1 output vector measured by the isolated acoustic vector sensor at time t has the complex envelope represented as

$$\mathbf{x}(t) = \sum_{k=1}^{K} \mathbf{c}(\theta_k, \phi_k) s_k(t) + \mathbf{n}_0(t) = \mathbf{C}\mathbf{s}(t) + \mathbf{n}_0(t) \quad (2)$$

where $\mathbf{s}(t) \overset{\text{def}}{=} [s_1(t), \ldots, s_K(t)]^{\mathrm{T}}$, with the superscript $^{\mathrm{T}}$ denotes the transpose operator; $s_k(t)$ represents the kth signal's complex envelope; $\mathbf{C} \overset{\text{def}}{=} [\mathbf{c}(\theta_1, \phi_1), \ldots, \mathbf{c}(\theta_K, \phi_K)]$; $\mathbf{n}_0(t) \overset{\text{def}}{=} [n_1(t), \ldots, n_4(t)]^{\mathrm{T}}$ refers to the 4×1 additive zero-mean complex noise and is independent to all signals. Throughout the paper, it is assumed that $\mathbf{C}$ is of full rank. The assumption is required for all direction finding algorithms.

The inter-vector sensor spatial phase factor for the kth incident source signal and the pth acoustic vector sensor in the ℓth row is [4,6]

$$q_{\ell,p}(\theta_k, \phi_k) = \mathrm{e}^{\mathrm{j}2\pi \frac{x_{\ell,p}u_k + y_{\ell,p}v_k + z_{\ell,p}w_k}{\lambda}} = \mathrm{e}^{\mathrm{j}2\pi \frac{x_{\ell,p}u_k}{\lambda}} \mathrm{e}^{\mathrm{j}2\pi \frac{y_{\ell,p}v_k}{\lambda}} \mathrm{e}^{\mathrm{j}2\pi \frac{z_{\ell,p}w_k}{\lambda}} \quad (3)$$

where $(x_{\ell,p}, y_{\ell,p}, z_{\ell,p})$ is the spatial location of the pth acoustic vector sensor in the ℓth row. Denoting the components of spacing between adjacent sensors in a row as $(\Delta_x, \Delta_y, \Delta_z)$, we have

$$x_{\ell,p} = x_{\ell,1} + (p-1)\Delta_x \quad (4)$$

$$y_{\ell,p} = y_{\ell,1} + (p-1)\Delta_y \quad (5)$$

$$z_{\ell,p} = z_{\ell,1} + (p-1)\Delta_z \quad (6)$$

Then, the $4LP \times 1$ array manifold of the entire planar acoustic vector sensor array is

$$\mathbf{a}(\theta_k, \phi_k) = \begin{bmatrix} \mathbf{a}_{1,1}(\theta_k, \phi_k) \\ \vdots \\ \mathbf{a}_{1,P}(\theta_k, \phi_k) \\ \vdots \\ \mathbf{a}_{L,1}(\theta_k, \phi_k) \\ \vdots \\ \mathbf{a}_{L,P}(\theta_k, \phi_k) \end{bmatrix} = \begin{bmatrix} q_{1,1}(\theta_k, \phi_k) \\ \vdots \\ q_{1,P}(\theta_k, \phi_k) \\ \vdots \\ q_{L,1}(\theta_k, \phi_k) \\ \vdots \\ q_{L,P}(\theta_k, \phi_k) \end{bmatrix} \otimes \mathbf{c}(\theta_k, \phi_k) \quad (7)$$

where $\otimes$ symbolizes the Kronecker-product operator. It follows from (7) that

$$\mathbf{a}_{\ell,p}(\theta_k, \phi_k) = q_{\ell,p}(\theta_k, \phi_k)\mathbf{c}(\theta_k, \phi_k) \quad (8)$$

(*footnote continued*)
There exists other propagator-based direction finding algorithms using the pressure-sensor array. For example, Marcos et al. [37] proposed the orthonormal propagator algorithm for 1D direction finding, Wu et al. [39] derived the 2D direction finding algorithm with parallel shape array, and Tayem and Kwon [40] presented the 2D direction finding algorithm with an L-shape array.