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Noncircularity-exploitation in direction estimation of noncircular signals with an acoustic vector-sensor

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Abstract

The main motivation of using an acoustic vector-sensor in direction-of-arrival (DOA) estimation applications has been its unambiguous two-dimensional directivity, insensitivity to the range of sources, and independence of signal frequency. The main objection lies in its lack of geometry-redundancy and limited degree of freedom. Four thus emerged challenging tasks and the corresponding solutions by recurring to the redundancies in the nonvanishing conjugate correlations of noncircular signals are described in the paper: (1) fulfilling source decorrelation in a multipath propagation environment; (2) enhancing processing capacity to accommodate more signals; (3) suppressing colored-noise with unknown covariance structure; and (4) deriving closed-form approaches to avoid iteration and manifold storage. Simulation experiments are carried out to examine the associated DOA estimators termed as: (1) phase-smoothing MUSIC (multiple signal classification); (2) virtual-MUSIC; (3) conjugate-MUSIC; and (4) noncircular-ESPRIT (estimation of signal parameters via rotational invariance techniques), respectively.

Keywords: Antenna arrays; Array signal processing; Direction-of-arrival estimation

1. Introduction

Over the last decade, numerous algorithms have been developed for the problem of DOA estimation of signals with acoustic vector-sensors [1–8], though, mostly repeat the work accomplished for the scalar-sensor counterparts. A "complete" acoustic vector-sensor such as a vector-hydrophone consists of a pressure sensor and a collocated triad of three orthogonal velocity sensors. These four sensors together measure the scalar acoustic pressure and all three components of the acoustic particle velocity vector of the incident wave-field at a given point [1]. In contrast, an "incomplete" acoustic vector-sensor consists of a subset of the above four-component sensors, for example, a three-component hydrophone formed from two orthogonally oriented velocity hydrophones and a pressure hydrophone [5]. The scalar-sensor such as a pressure-hydrophone thus can also be viewed as a special incomplete acoustic vector-sensor. In this paper, we only consider the complete acoustic vector-sensor.

The angular diversity present in even a single acoustic vector-sensor results in an effective aperture for the task of DOA estimation. An acoustic vector-sensor may be treated as a special array comprising four or less elements, and it has been shown in [9] that two signals can be uniquely identified by a complete acoustic vector-sensor. In addition,

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the array manifold of an acoustic vector-sensor is frequency-independent and hence the attendant DOA estimation algorithms are insensitive to the signal bandwidth. Another interesting feature of uni-vector-sensor array manifold is its realness nature. Still, unambiguous 2D DOA estimation (joint estimation of azimuth and elevation angles) can be accomplished with merely one acoustic vector-sensor.

However, due to its limited degree of freedom and lack of sensor-doublets, uni-vector-sensor based DOA estimation may encounter great difficulties in several important practical applications such as multipath propagation, heavy co-channel interferers, and colored-noise contamination, etc. Moreover, scalar-sensor counterparts for solving these mentioned problems do not seem to be available since most existing schemes devised for scalar-sensor arrays require the use of sensor-doublets or impose certain constraints on sensor arrangement—both of which are impossible for the case of an acoustic vector-sensor. Thus, developing effective DOA estimation algorithms especially for the aforementioned practical considerations is of critical importance for the popularity of using one vector-sensor for DOA estimation. To this end, we herein discuss the subspace-based methods for uni-vector-sensor DOA estimation, with focus on the next four topics: (1) aperture-preservable source decorrelation in a multipath propagation environment; (2) increasing the number of uniquely identified signals; (3) colored-noise cancellation; and (4) iteration-free approaches to reduce computation load, by recognizing and exploiting underlying noncircularity of noncircular signals such as rectilinear AM (amplitude modulated) and BPSK (binary phase shift keying) signals. During the last two decades, there has been an increasing interest in employing phase-coherent modulation techniques in underwater wireless communication systems. Phase-coherent PSK signals were demonstrated to be a viable way of achieving higher bandwidth efficiency over many of the underwater channels [27–29], which served as another motivation behind the present work. Some pioneering work on noncircularity exploitation in DOA estimation with scalar-sensors instead of vector-sensors can be found in [10–13].

The rest of the paper is organized as follows. In Section 2, we introduce the data model. In Section 3, we propose the phase-smoothing technique for DOA estimation of two coherent signals. We then present in Sections 4, 5, and 6 the virtual-MUSIC (for localizing more than two signals), the conjugate-MUSIC (for colored-noise suppression), the noncircular-ESPRIT (be close-form in nature), respectively. The simulation results are finally given in Section 7. Throughout the paper, we denote matrices and vectors by bold uppercase and bold lowercase letters. Superscripts "T," "H," and "*" stand for transpose, conjugate transpose, and conjugate, respectively. $\mathbf{I}_{M,N}$ and $\mathbf{O}_{M,N}$ denotes the $M \times N$ identity matrix and zero matrix, respectively. We will suppress the index when this does not lead to any confusion. Moreover, "$\mathbf{0}$" denotes zero vector, "E" denotes statistical expectation.

2. Statistical data model

2.1. Vector-sensor measurements

It is assumed that the acoustic wave is traveling in a quiescent, homogeneous, and isotropic fluid, and is from a source of azimuth θ and elevation ϕ, where $0 \leqslant \theta < 2\pi$ and $0 \leqslant \phi \leqslant \pi$ are respectively measured from the positive x-axis and the positive z-axis (see Fig. 1). Then, the "complete" acoustic vector-sensor's 4×1 array response vector in a free space equals [1]:

$$\mathbf{a}(\theta,\phi) = \begin{pmatrix} \cos(\theta)\sin(\phi) \\ \sin(\theta)\sin(\phi) \\ \cos(\phi) \\ 1 \end{pmatrix} = \begin{pmatrix} u_x \\ u_y \\ u_z \\ 1 \end{pmatrix}, \tag{1}$$

where u_x, u_y, and u_z are the direction cosines along the x-, y-, and z-axis, respectively. The above two-dimensional azimuth-elevation directivity is inherently real-valued and independent of signal frequency and hence signal bandwidth. The array manifold for an acoustic vector-sensor is defined as $\mathcal{M} = \{\mathbf{a}(\theta,\phi)\colon\ (\theta,\phi) \in \Theta\}$, where Θ is the entire field of view.

2.2. Noncircular signal model

Assume that Q acoustic signals impinge upon the acoustic vector-sensor, then the vector-sensor output is given by

$$\mathbf{r}(t) = \sum_{p=1}^{Q} \mathbf{a}_p s_p(t) + \mathbf{n}(t) = \mathbf{A}\mathbf{s}(t) + \mathbf{n}(t), \tag{2}$$