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Harmonic tonal detectors based on the BOGA

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ABSTRACT

Tonals generated by machineries with rotating elements typically have a harmonic structure with unknown fundamental frequencies, amplitude, harmonic order and phase. Detecting this type of signals is of great importance to numerous engineering applications. In the frequency domain, tonals are represented by a few harmonic frequencies, which appear in blocks, related to one or more fundamental frequencies. This block-sparsity property of the frequency content suggests alternative ways to recover and detect tonals by using sparse signal processing techniques. Motivated by the success of the block orthonormal greedy algorithm (BOGA), new detection architectures, which require no prior information about the number of the fundamental frequencies, are proposed for robust tonal detection in low signal to noise ratio (SNR) environments. The distributions of the test statistics of detection architectures are firstly analyzed theoretically and comprehensively based on the theory of order statistics. Detection performances are also analyzed and compared theoretically and experimentally. Significant improvements on detection performance in low SNR environments are shown over the conventional detectors that do not consider the harmonic structure and the sparsity of the tonals.

1. Introduction

The detection of acoustic signals produced by the motorized vessels or vehicles is needed for various Sonar applications. Acoustic signals in complex underwater environments are usually contaminated by ambient sounds due to seismic disturbances, oceanic turbulence, and various anthropogenic sources. For simplicity, the ambient noise is generally assumed to be a white Gaussian stationary process and the underwater sources, produced by rotating machineries such as shafts, blades and propellers, are typically modeled as a periodic envelope multiplying broadband noise. This audible phenomenon has been widely exploited to extract useful information, such as the number of blades and rotational rate [1]. Demodulated-noise (DEMON) processing is commonly used to obtain the required information based on the Fourier analysis, in which the received signals are presumed to have a harmonic line spectrum, i.e., a series of discrete lines or tonals that are harmonically related [2]. In [3], the received signal, $\mathbf{x}(t)$, is defined as cavitation noise, $\mathbf{s}(t)$, plus white Gaussian stationary ambient noise $\mathbf{v}(t)$:

$$\mathbf{x}(t) = \mathbf{s}(t) + \mathbf{v}(t) = \mathbf{m}_{\omega}(t)\mathbf{c}(t) + \mathbf{v}(t)$$

where $\mathbf{m}_{\omega}(t)$ is the periodic modulating signal with fundamental frequency ω determined by the motion of the rotating machineries, and $\mathbf{c}(t)$ is assumed to be stationary and change slowly with time. Within a short time period, we can reasonably assume that $\mathbf{c}(t)$ is a constant. Since $\mathbf{m}_{\omega}$ is presumed to be periodic, the spectrum of the acoustic signal contains several harmonically related narrow-band peaks (or

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tonals) which can be modeled as sinusoids. Because engines typically have more than one rotating or vibrating elements, these harmonics appear in different blocks related to their fundamental frequencies determined by the period of the rotating elements.

Several types of tonal detectors exist in the literature. The most common technique, low frequency analysis and recording (LOFAR) [4], averages the spectra of data segments after noise-mean removal and normalization. Wagstaff's integration silence processor (WISPR) [5] achieves better performance by integrating the spectrum of each data segment nonlinearly based on the fluctuations between signal and noise. Unlike the LOFAR and WISPR, which perform simple integration, a generalized likelihood ratio test based on power spectrum (PGLRT) [6] optimally integrates the power spectra of data segments according to their statistical properties. Although the PGLRT is optimal from the perspective of statistical properties, it loses the phase information of the signal by squaring the amplitude of the discrete Fourier transform (DFT). The generalized likelihood ratio test based on coherent integration (CGLRT) [7] was then proposed to make full use of the phase information to achieve coherent signal integration for improvement on the detection performance.

Previously reported detectors only focus on the detection of a single spectrum line without sufficiently considering the harmonic structure. It is generally assumed that observation time is long enough such that incoherent and coherent integration can be applied to increase the SNR. This paper considers more critical application environments with very low SNR and short observation duration, in which $\mathbf{c}(t)$ is considered to be constant. In such cases, most detectors based on long time integration cannot provide satisfactory performance. Conventionally, one may try to make use of the concept of a generalized matched filter (GMF) to achieve the optimal detection performance under the assumption that the signal space is known [8]. However, the only prior information is that these tonals are harmonically related to their own fundamental frequencies. Since the number of the fundamental frequencies and the harmonic order associated with each fundamental frequency are unknown, it becomes impossible to implement the GMF technique.

This paper will show that the harmonic tonals associated with different fundamental frequencies are block-sparse in nature [11]. That is, only a few harmonic blocks of the tonals are nonzero. In [11], audio signal is decomposed successfully by the Matching Pursuit (MP) with a block structure and a detector based on the estimation of the block-structured MP is designed particularly for music signals. Inspired by [11], our basic idea is to take the block-sparsity into consideration to find the support of the signal and then design the detector for harmonic tonals in Sonar application from a statistical signal processing perspective. Block-sparsity has been recently exploited for many applications such as: motion segmentation [9], multiband signal reconstruction [10], and harmonic decomposition of audio signals [11]. Algorithms, such as $l_{p,q}-$norm based convex optimization, group lasso [12], block orthogonal greedy algorithm (BOGA) [13–16], as well as the block-sparse Bayesian learning (BSBL) algorithm [17], have been reported in the literature to solve the problem with block-sparsity. It is also noted that block-sparsity has already used in [28,29] for flexible multi-pitch estimation without prior knowledge of numbers of pitches and their harmonics in speech and audio processing. Other fundamental frequency and model order estimation methods can be found in [26,27,30] and the references therein. In this paper, the BOGA method is used due to the following two reasons. Firstly, since group lasso algorithm requires convex optimization and BSBL requires an iterative expectation maximization (EM) procedure, both methods are much more expensive in computation complexity compared to the BOGA. Secondly, since the BOGA method finds the signal support in successive steps, it is easy to insert a sequential detection procedure into each step of the BOGA. Two BOGA based architectures are proposed. The first one is a subspace harmonic detector in which the BOGA is firstly applied to find the signal space and then the energy detector is used to detect the existence of the signal. By inserting a sequential detection procedure into each step of BOGA, the second one is a sequential harmonic detector based on order statistics. Both proposed detectors accumulate the energy from the fundamental frequencies and their associated harmonics to achieve robust detection performance in low SNR environments. There are three main contributions of this paper. The first one is to formulate the harmonic tonals by the block-sparse signal model and suggest using the block sparse recovery techniques in harmonic detection and estimation. The second contribution is that two new detection architectures are proposed by modifying the BOGA which theoretically uses the maximal signal energy in the tonal detection with no prior information of the number of harmonic sets. The theoretical analysis of the test statistics and the detection performances using the theory of the order statistics are given comprehensively, which is the third contribution of this paper.

This paper is organized as follows. In the next section, the harmonic signal model, dictionary construction and a harmonic signal model with block-sparsity are presented. Based on the constructed dictionary, two detection architectures are proposed in Section 3. By studying the test statistics and thresholds under the null hypothesis, the performances of the proposed architectures are also analyzed in this section. Some issues on the proposed architectures are discussed in Section 4. The results of simulations are given in Section 5 to show the effectiveness of the proposed detection architectures. Finally, Section 6 discusses some limitations of the reported architectures and addresses the possible future work.

Throughout the paper, we denote the variables by lowercase and uppercase letters, e.g., k and K, the vectors by bold lowercase letters, e.g., $\mathbf{u}$ and its lth element $\mathbf{u}(l)$, and the matrices by bold uppercase letters, e.g., $\mathbf{D}$ and its lth column by $\mathbf{d}_l$. Given a vector $\mathbf{u}$ constructed by a concatenation of blocks of the same size, its lth block is denoted by $\mathbf{u}[l]$. For a given matrix $\mathbf{D}$, $\mathbf{D}^H$ and $\mathbf{D}^\dagger$ denote its conjugate transpose and pseudo-inverse, respectively. Finally we use $\|\bullet\|_q$, where $q=2,\infty$, to represent l_2 and $l_\infty-$norm.