Wideband Beamforming with Broad Nulls Based on Nested Array

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Abstract: A method for wideband beamforming with broad nulls of harmonic nested array is proposed. The harmonic nested array is composed of several uniformly-spaced linear subarrays, each of which processes an octave subband signal respectively. Nonuniform octave subband signals are implemented by general parameter filter banks with multirate method. Each subarray beamforming is carried out by space-frequency signal processing approach. We divide each octave subband into K frequency bins firstly. Secondly, the reference desired broad nulls pattern is designed with derivative constraints orthogonal method at the highest frequency bin. Thirdly, an IDFT on the samples of sampled the reference desired pattern with appropriate sample interval is performed to obtain the weightings for each frequency bin, then the DFT to find the pattern for corresponding frequency bin is taken. At last, combined all patterns of each frequency bin together the wideband pattern can be obtained. Each subarray is operating with the lowest rate in parallel. Weightings and patterns are realized by IDFT and DFT. These contribute to decreasing the computational load significantly and improving the speed and performances as well. Simulations show that the proposed beamformer is competent for broad nulls wideband beamforming with lower computation complexity. Copyright © 2013 IFSA.

Keywords: Broad null, Wideband beamforming, Subarray, Multirate method, General parameter filter banks, Nested array.

1. Introduction

There is considerable interest in wideband beamforming for applications in various areas such as radar, sonar, acoustics, radio astronomy, and communications. Previous research of wideband beamforming based on different element configurations can be divided into three major streams: space-time signal processing, space-frequency signal processing and fully spatial signal processing [1-3]. Among these structures, one frame using a set of harmonic nested arrays has become favorable, especially in microphone array signal processing [4-7]. The uniform linear array is consisted of several sets of uniform nested arrays. At the same time, received wideband signals by elements were divided into several subbands in terms of 1-octwav criterion for corresponding nested subarrays. The advantage of this structure beamformer are more quickly convergence speed of weights resulted from each subarray operating in parallel, less coupling among elements and lower
cost because of less element is needed compared with traditional uniform linear array.

For wideband beamforming, one problem is to assure the undesired signal in pattern null direction, especially interfering signal is moving or DOA estimating is not accurate enough. Broadened null is a common method. There are several broaden null methods that have been proposed for interference suppression [8-10].

In this paper, a multirate method with an efficient general parameter filter banks was adopted, and each subarray beamformer was operating at lowest sampling rate. Each subarray beamforming is carried out by space-frequency signal processing approach. We divide each octave subband into K frequency bins firstly. Secondly, the reference desired broad nulls pattern is designed with derivative constraints orthogonal method at the highest frequency bin. Thirdly, an IDFT on the samples of sampled the reference desired pattern with appropriate sample interval is performed to obtain the weightings for each frequency bin, then the DFT to find the pattern for corresponding frequency bin is taken. At last, combined all patterns of each frequency bin together the wideband pattern can be obtained. Each subarray is operating with the lowest rate in parallel. Weightings and patterns are realized by IDFT and DFT. The advantage of this approach is the loads of computational processing costs can be alleviated more efficiently.

This paper is organized as follows. In section 2, the background on nested array will be introduced briefly. In section 3, wideband beamforming with broad nulls will be described in detail. In section 4, simulation results and analysis will be presented. In last section, brief conclusions will be drawn.

2. Harmonic Nesting Structure

A harmonic nested array consists of a set of superimposed subarrays, each designed for a single octave as shown in Fig. 1. Assume that interesting frequency span is \([f_c, f_s]\). The bottom subarray is \(M\)-element uniform linear array, designed for the subband which frequency range is \([f_s/2, f_c]\). To avoid grating lobes, the interelement spacing \(d_i\) is at most half the wavelength of the highest frequency within the subband corresponding of this subarray, i.e. \(d_i = \lambda_s/2 = c/2f_s = d\), where \(c\) is the speed of propagation. The next subarray is nested with the first subarray with \((N+1)/2\) superimposed elements. The interelement spaced at \(d_s = \lambda_s = 2d\), which corresponds to half-wavelength spacing at \(f_s/2\). The third subarray spaced at \(d_i = 2\lambda_s = 4d\), which corresponds to half-wavelength spacing at \(f_s/4\). The fourth subarray spaced at \(d_i = 4\lambda_s = 8d\), which corresponds to half-wavelength spacing at \(f_s/8\). The additional subarrays are designed similarly until the lowest frequency \(f_c\) is covered or the element spacing limit is reached. We can see that the nested array is a subband sampling processor in spatial domain, which splits the wideband signal into several subband ones with an octave and process by corresponding subarrays.

![Fig. 1. Super-imposed configuration of harmonically nested array.](image)

3. Wideband Beamforming with Broad Nulls Based on Nested Array

3.1. Structure of Wideband Beamformer

The whole array processor used in this paper can be shown as Fig. 2. An octave passband analysis filter obanks used to getting one octave subbands from each subarray. \(\downarrow D_i\) is decimation by \(D_i\) and \(\uparrow D_i\) stands interpolation by \(D_i\). Signals received by each subarray are sampled in sampling rate \(f_s\). Each subarray is processed by its corresponding analysis filter \(H_i(z)\) \((i = 1,2,3,4)\), and then decimated by \(D_i\). After the decimation, the adaptive beamformer of each subarray operates at a lower sampling rate \(f_c\), where \(f_c = f_s/D_i\). Outputs of these beamformers are interpolated by the up-samplers \(D_i\) and combined via the synthesis filters \(F_i(z)\). In Fig. 2, analysis filters and synthesis filters are mutual and crucial in this
structure. Some advantages can be concluded from the nested array structure and multirate method as depicted above [5].

Fig. 2. Structure of the nested array with nonuniform subband multirate method.

According to the Fig. 2, each subarray requires an analysis filter and a synthesis filter to avoid liasing and imaging. With smaller bandwidth covered by each subarray, temporal multirate sampling is incorporated with the nested array via down-samplers and up-samplers. In order to obtain an octave frequency bandwidth filter banks, tree structure filter banks with two-channel maximum decimation general parameter filter banks were used [11]. Two-channel filter banks cascaded is more convenient approach. General parameter filter has not only infinite impulse response filter’s efficiency but also finite impulse response filter’s linear phase characteristic. The broad nulls wideband beamformer of each subarray is designed in details in next section.

3.2. Space-Frequency Wideband Beamforming

Some wideband beamforming method can be used to design broad nulls wideband beamforming for subarrays [1, 8-9]. The frequency method was adopted in this paper. We divide the output of each subarray into K frequency bins and use narrowband processing to create a pattern in the frequency. For one subarray operating frequency span \( f_a, 2f_a \), the centre frequency of each frequency bins is:

\[
f_k = f_a \left(1 + \frac{2k+1}{2K}\right), \quad k = 0, 1, \ldots, K - 1.
\] (1)

In order to obtaining broad nulls pattern over each octave, we first define a reference desired broad nulls pattern at \( f_a \) for a uniform linear array whose spacing is \( \lambda_a / 4 \) (the design details is shown in the next section), so we need to consider the beam pattern over twice the visible region. For each of the frequencies in (1), we sample the beam pattern at:

\[
u_n = \frac{nc}{Nd_a},
\] (2)

where \( c \) is the velocity of propagation in the medium, \( c = 335.28 \) m/s in this paper. Assume the number of each subarray element \( N \) is odd. \(-\frac{(N-1)}{2} \leq n \leq \frac{(N-1)}{2}, \quad 0 \leq k \leq K - 1\). We perform an Inverse Discrete Fourier Transform (IDFT) on the samples to obtain the weightings for that frequency bin \( f_k \). We then take the DFT to find the beam pattern for frequency bin \( f_k \). When \( k \) increases from 0 to \( K-1 \), the weightings of \( K \) frequency bins will be obtained, and then the beam pattern of whole frequency spans will be obtained too.

3.3. Desired Reference Frequency Broad Nulls Pattern Synthesis

In this section, the reference frequency broad null pattern is designed. We adapt the method of orthogonal method under derivative constraints [10].

Assume there are \( M_0 (M_0 \leq N -1 ) \) independent nulls at \( M_0 \) position on the desired pattern, then pattern is

\[
F(u_n) = \sum_{z=0}^{K} B_{z} \psi_{z} (u_n) = \psi^T B = 0,
\] (3)
where \( N \) is the number of subarray element, \( u = \pi \sin \theta \), angle \( \theta \) is measured from normal of linear array to direction of impinging plane wave signal. \( \{ \varphi_s(u) \}_{n=1}^{N} \) is the orthogonal basis, \( B_i \) is the \( \varphi_s(u) \) projection of \( F(u) \). Where \( m = 1, 2, \cdots M_0 \), Define \( N \times M_0 \) constraint matrix \( C_0 \).

\[
C_0 = \begin{bmatrix}
\varphi_1(u_1) & \varphi_2(u_1) & \cdots & \varphi_N(u_M) \\
\vdots & \vdots & & \vdots \\
\varphi_1(u_n) & \varphi_2(u_n) & \cdots & \varphi_N(u_M)
\end{bmatrix}
\]

In order to broaden nulls, derivative constraints can be imposed on null positions of the initial pattern. Firstly, assume first derivative of the pattern with respect to \( u \). \( \Omega \) is the subset of the \( M_0 \) locations where we want the derivative to equal zero and contains \( M_1 \) points. Secondly, define \( N \times M_1 \) constraint matrix \( C_1 \) which element is \( \varphi^{(r)}(u) \). The \( r \)-th type of constraint is the \( r \)-th derivative of the pattern with respect to \( u \). For a linear array, this corresponds to

\[
\frac{d^r F(u)}{d u^r}\bigg|_{u=n} = \frac{d^r \left[ \sum_{n=1}^{N} B_n \varphi_n(u) \right]}{d u^r}\bigg|_{u=n} = \sum_{n=1}^{N} B_n \frac{d^r \varphi_n(u)}{d u^r}\bigg|_{u=n},
\]

where \( i \in \Omega \), \( \Omega_{r-1} \) is a subset of \( \Omega \) and \( M_r \) points. Define \( N \times M_r \), constraint matrix \( C_r \) which element is \( \varphi^{(r)}(u) \). Then, the total constraints matrix is \( C = [C_0 \ C_1 \cdots C_r] \), assume \( M_r = M_0 + M_1 + \cdots + M_r \) and \( M_r < N \). If the columns of \( C \) are linearly independent, then \( C^T C \) will not be singular. Now Lagrange multiplier is can be used to get the final weights [10].

4. Simulations and Discussions

The performance of the broad nulls wideband beamformer of nested array is evaluated in this section. Assume that the number of element \( N \) of each subarray is 11, the frequency spans of desire signal, noise and interference are 0.5 kHz-8 kHz. Each individual filter is Butterworth general parameter filter with order of 16 and 2 pair of complex zeroes, and the original amplitude fluctuation within pass band is 0.5 dB. There are 2 complex zeroes at \( \omega = \pi \) and \( \omega = 0 \) for lowpass filter and highpass filter, respectively [11]. There are four subarray as shown in Fig. 1, so the first subband frequency span is 4 kHz-8 kHz, the second is 2 kHz-4 kHz, the third is 1 kHz-2 kHz and the fourth is 0.5 kHz-1 kHz. The corresponding sampling rate \( f_s \) is 16 kHz, 8 kHz, 4 kHz and 2 kHz respectively. In this paper \( K \) is 16 for each subarray. The four reference frequency broad null patterns are designed at frequency 8 kHz, 4 kHz, 2 kHz and 1 kHz respectively.

Assume that one desired pattern of the whole frequency spans is the maximal directivity at \( \theta = 0^\circ \), there are one narrow null at \(-40^\circ\), one broad null from \(29^\circ \) to \(30^\circ \), another broad null from \(68^\circ \) to \(72^\circ \). We set zero order, second order and third order derivative constraints at \(-40^\circ\), \(30^\circ\) and \(70^\circ\) respectively.

Fig. 3 shows the desired reference frequency bin broad nulls pattern by the derivative constrained orthogonal approach. It obvious that pattern meets designing requirement well.

The last broad nulls wideband pattern of nested array was shown in Fig. 4. It obvious that the desired signal can be received without distortion and the interference signal within broad nulls span can be attenuated more than 80 dB in all frequency range. Moreover, main beamwidths of different frequency are almost invariable. It can be seen that their patterns are almost same in mainlobe region, but in sidelobe, the aliasing will be severe slightly as the bandwidth of subband signal increasing, it can be reduced through increasing the number of frequency bins \( K \).

![Fig. 3. Desired reference frequency bin broad nulls pattern.](image-url)
5. Conclusions

A method of wideband beamforming with broad nulls based on multirate space-frequency signal processing and derivative constraints orthogonal method for harmonic nested array is proposed. Nonuniform octave subband signals are implemented by general parameter filter banks with multirate method. Each subarray beamforming is carried out by space-frequency signal processing approach. The reference desired broad nulls pattern is designed with derivative constraints orthogonal method at the highest frequency bin. Weightings and patterns are realized by IDFT and DFT. Simulations show that the proposed beamformer is competent for broad nulls wideband beamforming with lower computation complexity.

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