DESIGN OF BROAD-BAND CIRCULAR RING MICROPHONE ARRAY FOR SPEECH ACQUISITION IN 3-D

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ABSTRACT

In this paper we address the problem of speech acquisition using concentric circular ring array with omnidirectional microphones. The goal of our design is to achieve a specified sidelobe level in the beampattern. A previous work by Stearns [1] proposed a method to achieve low sidelobe level for continuous concentric ring antenna. The method assumes narrow-band signal and uses continuous ring and therefore not suitable for speech application. This paper generalizes Stearns's method to broad band signal acquisition in 3-D using a discrete ring array. A compound ring structure is employed to reduce the number of rings involved. An example is given to demonstrate our design method. The proposed design method can be used to produce a nonadaptive beamformer with a certain desirable beampattern, or to generate the weight constraint corresponding to the white-noise beampattern in an adaptive beamformer.

1. INTRODUCTION

In recent years, microphone arrays have found increasing applications in hands-free speech acquisition scenarios such as teleconference, teleworking, automobile voice pick up, etc. The speech frequency range is $500 - 4KHz$ and the highest frequency to the lowest is 8. Hence a broad-band beamformer is necessary for speech acquisition. An ideal broad-band beamformer should have frequency independent beampattern. However, this is very difficult, if not impossible, to achieve in practice. A more practical goal is to achieve similar width in the main lobe and sidelobe level over the desired frequency range for broad-band beamforming. A large Uniform Linear Array(ULA) with densely placed microphones can be used for broad-band beamforming. However it is considered inefficient since a large amount of microphones are required. The design of broad-band beamformers based on linear array can be classified into two categories: unequally spaced array and compound array. Unequally spaced array [2, 3], also called "thinned" array, aims at reducing the density of array elements by manipulating the locations and weights of the array elements. Compound array [4, 5], on the other hand, uses a set of subarrays for different subbands in a wide frequency range. The element locations are carefully chosen so that different subarrays may have some of their elements superimposed, resulting in saving in total amount of array elements.

The previous methods described above for broad-band beamforming are based on linear array. The ambiguity set of Direction Of Arrival (DOA) for a linear array is a cone wrapping around itself [6]. This ambiguity will increase the background noise level in the beamformer output and pick up some directional noise coming through the ambiguity direction. Two dimensional(2-D) array is generally superior to linear array for 3-D beamforming in that the amount of ambiguity is reduced to 2 DOAs.

Among 2-D arrays, circular array has received considerable interest for its symmetric and compact structure. Because of the 2-D and nonlinear configuration of circular array, previous techniques based on linear broad-band array design is not applicable.

Stearns [1] has proposed a method to achieve low sidelobe level for continuous concentric ring antennas by optimizing the weights among different ring's beampattern through the Fourier-Bessel series inversion. A recent work by Vu [7] explored sidelobe control in a circular ring array to improve performance. His method, however, is only effective for broadside direction beamforming. In [8], Kumar *et al.* proposed a design of low sidelobe circular ring array by element radius optimization, which is suitable for narrow-band beamforming only.

In this paper, we generalize Stearns's method for broad-band beamforming in 3-D and deduce the discrete ring array for this application. We further apply a compound ring array design to reduce the number of rings and make the discrete circular array suitable for speech acquisition.

The paper is organized as follows. Section 2 introduces the related concepts of circular ring beamforming. Section 3 briefly reviews Stearns's design for continuous ring antennas. The generalization of Stearns's method for broad-band beamforming using discrete ring array is described in Section 4 and the compound ring design is also presented. Section 5 gives a design example using the proposed method. A summary is given in Section 6.

2. BEAMPATTERN OF A CIRCULAR RING ARRAY

A ring array is composed of N elements equally spaced along a circle of radius R as depicted in Fig. 1. Assuming (θ_0, ϕ_0) is the signal's arriving direction, the delay-and-sum beampattern of such a ring array is [9]:

$$f(\theta, \phi, k) = \frac{1}{N} \sum_{i=1}^{N} e^{-jkR[\sin\phi_0\ \cos(\theta_0 - v_i)\ -\ \sin\phi\ \cos(\theta - v_i)]} \tag{1}$$

where $j = \sqrt{-1}$, $v_i = 2\pi i/N$ is the ith element's azimuth angle, $k = 2\pi/\lambda$ and λ is the wavelength of the signal.

Eq. (1) can be expressed as a Bessel function series [9],

$$f(\theta, \phi, k) = J_0(kR\rho) + 2\sum_{q=1}^{\infty} j^{Nq} J_{Nq}(kR\rho)\cos(Nq\xi) \tag{2}$$

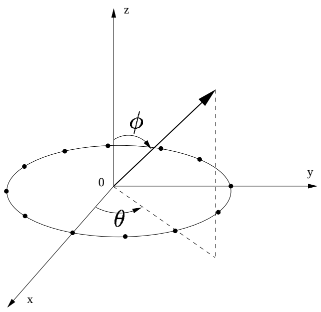

Fig. 1. Geometry of a ring array

where $J_n(x)$ is the nth order Bessel function of the first kind and

$$\rho^2 = (\sin\phi\cos\theta - \sin\phi_0\cos\theta_0)^2 + (\sin\phi\sin\theta - \sin\phi_0\sin\theta_0)^2 \quad (3)$$

$$\xi = \arccos\frac{\sin\phi\ \cos\theta\ -\ \sin\phi_0\cos\theta_0}{\rho}. \quad (4)$$

For an M concentric ring array, the synthetic beampattern is the weighted sum of the beam patterns from different rings:

$$\begin{aligned} f(\theta,\phi,k) \quad &= \sum_{m=1}^{M} w_m[J_0(kR_m\rho) \\ &+2\sum_{q=1}^{\infty} j^{Nq}J_{Nq}(kR_m\rho)\cos(Nq\xi)] \end{aligned} \quad (5)$$

where w_m is a real number that represents the weight for the beampattern of the mth ring.

The beampattern for M concentric continuous rings has the same form as in (5) only without the terms of the higher order Bessel functions [9],

$$f(\theta,\phi,k) = \sum_{m=1}^{M} w_m J_0(kR_m\rho). \quad (6)$$

In continuous ring beamformer, its beampattern is a weighted sum of various zero order Bessel function. The summation can result in high sidelobe level if the weights are not chosen carefully. Thus w_m plays a central role in the synthetic beampattern for circular ring beamformer. As will be explained in the next section, Stearns's method uses the Fourier-Bessel series to select w_m in (6) to achieve a desired low sidelobe level. For a discrete ring array, its beampattern is complicated by the inclusion of high order Bessel function. The selection of w_m for discrete ring array is a subject to be addressed in this paper.

3. CONTINUOUS RING BEAMFORMER

For any function $g(x)$ continuous in $[0, 1]$, it can be expressed as a Fourier-Bessel series as [1],

$$g(x) = \sum_{m=1}^{\infty} A_m J_0(\delta_m x), 0 < x < 1 \quad (7)$$

where δ_m is the mth zero of $J_0(x)$ arranged in ascending order. The coefficients A_m are given by [1]

$$A_m = \frac{2}{J_1^2(\delta_m)}\int_0^1 \tau g(\tau)J_0(\delta_m\tau)d\tau. \quad (8)$$

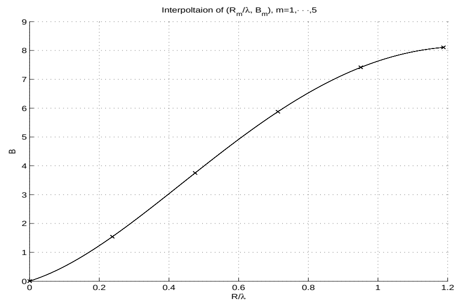

Fig. 2. Interpolation of $(R_m/\lambda, B_m)$, $m = 1, \cdots, 5$

Stearns's method is derived for a special case of 2-D beamforming in the x-y plane. In such case, $\phi = \pi/2, \phi_0 = \pi/2$ and ρ in (3) becomes

$$\rho = 2\sin(\frac{\theta-\theta_0}{2}). \quad (9)$$

Putting it into (6) gives

$$f(\theta,\phi,k) = \sum_{m=1}^{M} w_m J_0(2kR_m\sin(\frac{\theta-\theta_0}{2})). \quad (10)$$

$f(\theta,\phi,k)$ can be viewed as a truncated Fourier-Bessel series. If M is large enough then any $g(x)$ expressed as a infinite Fourier-Bessel series can be approximated by $f(\theta,\phi,k)$. In order to do this, the following mapping relationship between (7) and (10) need to be established,

$$x = \sin(\frac{\theta-\theta_0}{2}),\ \ \theta\in[\theta_0, 2\pi+\theta_0] \quad (11)$$

$$\delta_m = 2kR_m \quad (12)$$

$$w_m = A_m. \quad (13)$$

If $g(x)$ represents the desired beampattern, w_m calculated by using (13) and (8) will generate an approximation to this desired pattern.

(12) indicates that the first M zeros of $J_0(x)$ determines the radii of the M rings and this may be inconvenient in practice. An interpolation technique was used by Stearns to overcome this restriction. First, the accumulative value of A_m is obtained:

$$B_m = \sum_{j=1}^{m} A_j. \quad (14)$$

A set of points $(R_m/\lambda, B_m), m = 1,\ldots,M$ is interpolated as shown in Fig. 2, where $\lambda = c/f$ and f is the desired operating frequency. If it's desirable to have M equally spaced rings, the curve is resampled at M equally spaced points in the interval of $[0, R_M/\lambda]$. Denoting the new sampling points by $(R'_m/\lambda, B'_m)$, $m = 1,\ldots,M$, then a new set of weights is obtained by:

$$w'_m = A'_m = B'_{m+1} - B'_m. \quad (15)$$

w'_m now corresponds to the weight of the mth ring whose radius is given by R'_m. Notice that the radius of the Mth ring is kept unchanged with the value of

$$R_M = \delta_M/(2k). \quad (16)$$

This is to ensure that the array dimension remains to be the same. It's shown by Stearns that this resampling technique has negligible effect on the resultant beampattern.

4. PROPOSED BROAD-BAND CIRCULAR RING ARRAY

4.1. 3-D beamforming

Stearns's method can be generalized to 3-D beamforming by applying the specification of sidelobe level to a surface cutting through the look direction of the 3-D beampattern. When the look direction is the z-axis, the 3-D beampattern is symmetric with respect to the z-axis. Thus specification applied to such a surface is equivalent to specification applied to the entire 3-D beampattern. When the look direction deviates from the z-axis, the symmetry is distorted. However the sidelobe level will still be reduced through the method derived from Stearns. Our design chooses the cone surface defined by $\phi = \phi_0$ to be such a surface and the mapping relationship in (11) is generalized to

$$x = \begin{cases} \sin(\phi)/2 & \phi_0 = 0,\ \phi \in [0, \pi] \\ \sin(\phi_0)\sin(\frac{\theta-\theta_0}{2}) & \phi_0 \neq 0,\ \theta \in [\theta_0, 2\pi + \theta_0]. \end{cases} \quad (17)$$

4.2. Band broadening

Suppose that an M continuous ring beamformer operating at frequency f_0 has been obtained using Stearns's method. When the incoming frequency deviates from f_0, the beampattern varies accordingly and the sidelobe level will be higher than the desired value. The aim of our proposed broad-banding technique is to achieve similar sidelobe level over the input frequency range.

For the largest ring radius equation in (16), replacing k with $2\pi\lambda_0$ and rearranging it gives

$$\lambda_0 = 4\pi R_M/\delta_M. \quad (18)$$

When R_M is fixed, a different zero δ_P of $J_0(x)$ is related to a different wavelength by

$$\lambda' = 4\pi R_M/\delta_P. \quad (19)$$

(19) reveals that by associating R_M with a different zeros of $J_0(x)$, we can obtain some flexibility in the beamformer's operating frequency. The association of R_M to δ_P can be interpreted as the fact that we now approximate the desired pattern $g(x)$ in (7) by a truncated Fourier-Bessel series of P terms, instead of M terms. Using Stearns's interpolation technique, P points $(R_m/\lambda', B_m), m = 1, \ldots, P$ are available for interpolating a curve similar to the one in Fig. 2. Since the radii of the M rings are already fixed, the new curve is sampled at points corresponding to those fixed radii. A new set of weights is obtained for each ring that corresponds to a new operating frequency at

$$f' = (\delta_P/\delta_M)f_0. \quad (20)$$

When $\delta_P < \delta_M$, the working frequency is shifted to a lower frequency. We can expect that a truncated series will need at least certain number of terms, denoted as P_L, to approximate a desired pattern $g(x)$. On the other hand, when $\delta_P > \delta_M$, the working frequency is increased. A curve interpolated from a P-point set after re-sampling is reduced to a representation of a M-point set. There exists an upper limit for P, denoted as P_U. When $P > P_U$, the distortion resulting from under sampling will be unacceptable. Thus P has a range of $[P_L, P_U]$ that corresponds to a series of possible operating frequencies for the beamformer

$$f_p = (\delta_p/\delta_M)f_0,\ p = P_L, P_L + 1, \cdots, P_U. \quad (21)$$

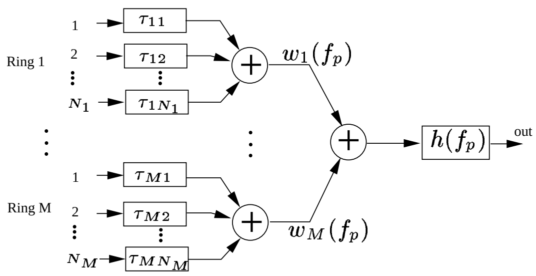

Fig. 3. Diagram of one subarray of our proposed beamformer. N_i denotes the number of elements on the ith ring and τ_{ij} denotes the time delay for the jth element in the ith ring, $w_i(f_p)$ and $h(f_p)$ are the weights and filter associated with f_p respectively.

By proper setting of w_m using the interpolation technique, similar beampattern can be achieved at those frequencies. The actual values of P_L and P_U depend on the desired pattern chosen and the number of rings used.

In the speech acquisition problem, the operating frequency range is from 500Hz to 4kHz. Suppose we have an M ring array that is chosen to achieve a desired beampattern at 500Hz. From (12) we have

$$\delta_M = 2\pi R_M/\lambda_{500Hz} \quad (22)$$

To extend the desired beampattern to 4kHz, the beampattern of the Mth ring will become a term in the Fourier-Bessel series associated with a zero near

$$x = 2\pi R_M/\lambda_{4kHz} = 8\delta_M.$$

$J_0(x)$ has the property that its zeros appear with an approximate period of 2π. So $x = 8\delta_M$ is roughly the $(4\delta_M/\pi)th$ zero. Setting $M = 6$, then $4\delta_M/\pi \approx 23$. When a Chebyshev function is used as the desired pattern, the P_U value for $M = 6$ from experiment is 11, which is well below 23. Thus the under sampling effect will be severe. This exposes the limitation of our band broadening technique for signal with wide frequency range as speech. Adding more inner rings to solve the under sampling problem is not a favorable option because of its inefficiency. To make the speech array efficient, we assimilate the compound array design used for linear array to improve our design.

The compound array is composed of subarrays for different frequency subbands. Within each subband, the proposed band broadening technique will be used to cover more frequencies. Fig. 3 shows the diagram of one subarray in a subband of the proposed method. The output of one subarray is summed over all p, where p denotes the index of all operating frequencies in one subband. Output from different subbands are summed to generate the output of the broad-band beamformer.

4.3. Broad-band discrete ring array

The discrete ring array's beampattern in (5) differs from the continuous ring beampattern in (6) in the additional higher order Bessel function terms. Thus the discrete ring beampattern is not a truncated Fourier-Bessel series as defined in (7) and can't be used to approximate a desire pattern without first removing the effect of the higher order Bessel functions.

From the properties of Bessel function, $J_0(x)$ has a mainlobe at $x = 0$ and decreasing sidelobes toward $x = \infty$. Higher order Bessel functions only have sidelobes and the distances between the origin and their first sidelobes increase with the order.

A 3-D beampattern has a visible region in terms of certain ranges in θ and ϕ. Given a Bessel function $J_0(\delta_m x)$ with x mapped to θ and ϕ as in (17), the visible region becomes $[-\delta_m/2, \delta_m/2]$ for $\phi_0 = 0$ or $[-\sin(\phi_0)\delta_m, \sin(\phi_0)\delta_m]$ for $\phi_0 \neq 0$. Suppose the location of the first sidelobe of a higher order Bessel function $J_{Nq}(x)$ in (5) is at $x = \pm X_{Nq}$. By choosing N large enough so that

$$X_{Nq} > \begin{cases} \delta_m/2 & \phi_0 = 0 \\ \sin(\phi_0)\delta_m & \phi_0 \neq 0. \end{cases} \quad (23)$$

then $J_{Nq}(x)$ will not affect the sidelobe level of the beampattern and the discrete beampattern can be well approximated by $J_0(x)$. The proposed broad-band beamforming method can be carried on to a discrete ring array.

(23) shows that smaller m value results in smaller visible region. Thus less elements are needed on inner rings. This observation can be served as a useful guideline in ring array design.

5. A BROAD-BAND CIRCULAR MICROPHONE ARRAY FOR SPEECH ACQUISITION

To illustrate our method, we consider a design problem for speech acquisition. To cover the speech frequency range from $500Hz$ to $4kHz$, two subarrays initially operating at $1kHz$ and $2kHz$ respectively are first obtained. Each subarray is composed of 6 equally spaced rings. Enlarging the size of the $1st$ subarray by 2 will give the $2nd$ subarray. Half of the inner rings can be reused through the compound ring concept and the total number of rings is 9. The normalized radii of the rings with respect to the first are: $[1, 2, 3, 4, 5, 6, 8, 10, 12]$. The largest ring's radius is $0.475m$, which is moderate.

A Chebyshev function with $-30dB$ sidelobe level is used as the desired beampattern. For a subarray initially operating at f_0, we found that P_L and P_U in (21) are 4 and 11 respectively. Using (21) all possible operating frequencies are listed in Table 1. Taking the bandwidth of the filter associated with each frequency into consideration, most of the speech frequency range is covered. For overlapped frequency range in the two subarrays, we will choose the subarray with better performance in terms of sidelobe level and mainlobe width. Among those operating frequencies, the highest frequency $(\delta_{11}/\delta_6)f_0$ requires the most microphones on each ring, which is found by (23) to be $[7, 14, 19, 23, 27, 32]$ for ring 1 to 6 respectively. Since the even number rings in the first subarray can be used by the second subarray, the total number of microphones needed is: $7 + 14 + 19 + 2 \times (23 + 27 + 32) = 204$.

Table 1. Possible operating frequencies $f_p = (\delta_p/\delta_6)f_0$.

p	4	5	6	7	8	9	10	11
Subband 1 f_p (kHz)	0.65	0.83	1	1.17	1.35	1.52	1.70	1.87
Subband 2 f_p (kHz)	1.31	1.65	2	2.35	2.70	3.04	3.40	3.74

Assume the arriving direction of the signal is $(\theta_0 = \pi/4, \phi_0 = 3\pi/8)$. For the purpose of illustration, the surface $\phi = 3\pi/8$ through the look direction is presented as a sample of the 3-D beampattern. The beampatterns for all possible operating frequencies in one subband are shown in Fig. 4. The beampatterns for another subarray are identical. As can be seen from the figure, the beampatterns fulfil the design objective of $-30dB$ sidelobe level. In the experiment, we haven't observed higher sidelobe level in other sampling surfaces of the 3-D beampattern.

6. CONCLUSIONS

In this paper we generalized Stearns's method for the design of a low sidelobe broad-band beamformer using circular ring array.

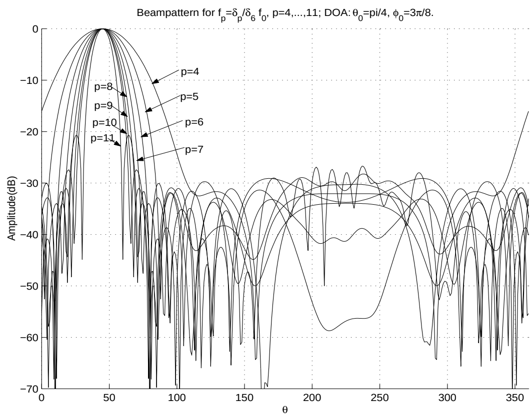

Fig. 4. Beampattern of discrete ring array at frequency $(\delta_p/\delta_6)f_0,\ p = 4, \cdots, 11$ in one subband.

Our contribution in the design includes deriving a band broadening technique to cover more frequencies, and establishing the conditions under which the continuous ring design can be used in discrete ring array. Furthermore, for signal with large broad-band ratio like speech, we propose to use a compound array structure to increase the efficiency of the circular ring array design. Through the analysis, some guidelines in choosing the radius and number of elements of on each ring are given. The proposed design method yields satisfactory results as corroborated by a design example.

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