

Optimizing the planarity of sound zones

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ABSTRACT

Reproduction of personal sound zones can be attempted by sound field synthesis, energy control, or a combination of both. Energy control methods can create an unpredictable pressure distribution in the listening zone. Sound field synthesis methods may be used to overcome this problem, but tend to produce a lower acoustic contrast between the zones. Here, we present a cost function to optimize the cancellation and the plane wave energy over a range of incoming azimuths, producing a planar sound field without explicitly specifying the propagation direction. Simulation results demonstrate the performance of the methods in comparison with the current state of the art. The method produces consistent high contrast and a consistently planar target sound zone across the frequency range 80-7000Hz.

1. INTRODUCTION

In the mid 1990s, Druyvesteyn [1] proposed the concept of personal sound zones. Since then, array signal processing for the creation of sound zones has emerged as a key sub-topic of sound field control. Fundamentally, at least two kinds of region must be created by the loudspeaker array - the target zone, where the sound pressure reaches a certain target level, and the dark zone, a region of cancellation where the audio program delivered to the target zone is attenuated. An independent audio system then can be created by superposition, as realized in [2].

The development of sound zones in the literature has seen the emergence of techniques which broadly fall in to two categories. One technique, with its heritage in wave-field synthesis, is to precisely specify the sound field controlled by the array. In this manner, a target sound field can be defined and the dark zone created by attenuating the sound pressure magnitudes for that region. Such control has been considered both analytically based on sound field coefficient translation in 2D (using line sources) [3, 4, 5] and 2.5D (using point sources) [6], and by an optimized pressure matching (PM) to directly minimize the error between a discretized desired sound field and that reproduced by the array [7]. These methods often require many loudspeakers, although recent work has given attention to this [8]. Typically, a plane-wave is specified as the desired field, although any sound field could be synthesized.

Alternatively, the energy in the zones can be controlled, either via a beamforming approach, or using an energy cancellation based optimization approach. In 2002, Choi and Kim presented brightness control, an optimized beamformer for focusing the energy in a particular direction, and acoustic contrast control (ACC), an energy cancellation method creating an extended region of significant attenuation [9]. Various applications of this work have been investigated for the personal audio scenario, including for PC users [10, 11], aircraft passengers [12, 13], and users of mobile devices [14, 15]. An alternative cancellation method known as acoustic energy difference maximization (AEDM) was proposed in [16] with a modified cost function to avoid the matrix inversion and allow for precise control of the array control effort.

Owing to the nature of the respective cost functions, they have distinctive performance characteristics. The energy cancellation methods can produce excellent acoustic contrast (cancellation) between the zones, offering great potential for sound zone reproduction, yet the phase in the target zone is uncontrolled. Consequently, multiple plane wave components impinge on the zone from various directions, which may create highly self-canceling waves or other undesirable audio artifacts, as noted in [6] and quantified in [17] via the planarity metric recently proposed by Jackson & Jacobsen [18]. The synthesis approaches are able to resolve this issue, but often at the

cost of some contrast performance and with high array effort. Furthermore, these methods are subject to spatial aliasing problems as frequency increases, with an upper frequency bound for accurate reproduction [19] (which is required for good cancellation).

Accordingly, recent advances in the literature have included hybrid methods which attempt to recreate a plane wave in the target zone whilst using an energy cancellation approach for the dark zone. Betlehem & Teal devised a constrained optimization approach based on PM to constrain the dark zone energy without specifying a desired field for that zone [20], and similar formulations have been proposed based on a hybridization of PM with ACC [21] and with AEDM [22]. Such hybrids have been shown to be effective at relatively low frequencies for reproducing planar sound fields with good contrast between the zones. However, in each case, the target sound field must be specified by the designer.

Whilst in some cases reproduction of specific plane wave components may be necessary (e.g. for spatial audio, due to the potential of reproducing any given sound field by superposition), specifying a plane wave is by no means the only satisfactory propagation pattern that the array could achieve. However, plane wave sound fields exhibit other advantageous properties such as good homogeneity of sound level across the zone and the avoidance of self-cancellation problems. Other methods have considered the manipulation of intensity in a single zone (with no corresponding cancellation region), for instance in [23] the intensity based on adjacent microphone responses in a zone is spatially averaged, optimized and controlled, and in [24] a plane wave is reproduced by focusing the plane wave energy towards a point in the wavenumber domain.

Here, the intensity is estimated using a superdirective beamforming approach that could be applied to any microphone array (rather than depending on a particular geometry) and is spatially averaged, applied to the target zone where a dark zone is also created. We propose a novel cost function ‘planarity control’ for sound zone optimization, where the incoming plane wave direction with respect to the target zone is constrained over a range of angles, rather than a single one. In this way, a planar sound field can be reproduced (alongside excellent cancellation) but the optimization is free to find the best plane wave direction.

In section 2, the evaluation metrics and existing sound

field control methods are introduced. The planarity control cost function is introduced in section 3. The performance of the method is demonstrated via simulations in section 4, following which the conclusions are drawn.

2. BACKGROUND

A sound zone system comprises an array of loudspeakers and a number of microphones sampling the sound field in each zone. For a single frequency, the source weight vector is written as $\mathbf{q} = [q_1 \ q_2 \ \dots \ q_L]^T$, where there are L sources and q_l describes the l th loudspeaker’s complex source strength. The vectors of pressures at the microphones in each zone can likewise be written. Here, we consider two zones, A and B; $\mathbf{p}_A = [p_1 \ p_2 \ \dots \ p_M]^T$ and $\mathbf{p}_B = [p_1 \ p_2 \ \dots \ p_N]^T$, where there are M microphones in zone A and N in zone B, p_m is the complex pressure at the m th microphone in zone A and p_n is the complex pressure at the n th microphone in zone B.

For zone A, the plant matrix containing the transfer functions between the loudspeakers and the microphones in zone A is defined as \mathbf{G}_A , and the equivalent notation is used for \mathbf{G}_B . The pressure vectors for each zone are populated by the summation of the contribution of each loudspeaker at each microphone, written in vector notation as $\mathbf{p}_A = \mathbf{G}_A \mathbf{q}$ and $\mathbf{p}_B = \mathbf{G}_B \mathbf{q}$ for zones A and B, respectively.

2.1. Evaluation measures

In this section, the three evaluation metrics used for evaluation of the novel cost function are introduced. These measure the achieved zone separation, the extent to which the target zone sound field exhibits characteristics of a plane wave, and the physical cost of cancellation.

2.1.1. Acoustic contrast

Acoustic contrast is a spatially averaged summary measure for sound zone performance, and is commonly used in the cancellation literature to describe system performance. For zone A defined by M microphones, the spatially averaged squared pressure is

$$|\bar{p}|_A^2 = \frac{1}{M} \sum_{m=1}^M |p|_{A,m}^2, \quad (1)$$

and can be more suitably expressed in decibels as the sound pressure level relative to the threshold of hearing, $p_{ref} = 2\mu Pa$:

$$\bar{p}_{SPL_A} = 10 \log_{10} \left(\frac{|\bar{p}|_A^2}{|p_{ref}|^2} \right). \quad (2)$$

Likewise, the pressures \bar{p}_B and \bar{p}_{SPL_B} can be obtained. The acoustic contrast between target zone A and dark zone B is defined as the ratio of spatially averaged pressures in each zone due to the reproduction of program A:

$$contrast_{AB} = \bar{p}_{SPL_A} - \bar{p}_{SPL_B}. \quad (3)$$

2.1.2. Planarity

The planarity of the sound field is a physical measure recently proposed by Jackson and Jacobsen [18] to assess the extent to which a reproduced sound field resembles a plane wave. The reproduction error, often used in the sound field synthesis literature to quantify the performance of sound field synthesis methods, may rate a highly planar sound field very poorly if the plane wave direction does not coincide with the specified sound field. For sound zone reproduction at a single frequency, the absolute angle of the incoming plane wave is not important and the planarity property has been designed to test each plane wave component impinging on the microphone array. The energy distribution at the microphone array over each incoming plane wave direction $\mathbf{w} = [w_1 \dots w_l]$ is given by $w_i = \frac{1}{2} \boldsymbol{\psi}_i^* \boldsymbol{\psi}_i$, where $*$ denotes the complex conjugate, $\boldsymbol{\psi} = [\boldsymbol{\psi}_1 \dots \boldsymbol{\psi}_l]$ are the plane wave components at the i th angle, related to the observed microphone pressures by the steering matrix \mathbf{H} whose elements are determined by super-directive beamforming about the microphone array, as in [18],

$$\boldsymbol{\psi} = \mathbf{H}\mathbf{p}. \quad (4)$$

The elements of \mathbf{H} could alternatively be calculated using a spatial Fourier decomposition approach. The planarity metric can now be defined as the ratio between the energy due to the largest plane wave component and the total energy flux of plane wave components:

$$planarity_A = \frac{\sum_i w_i \mathbf{u}_i \cdot \mathbf{u}_i}{\sum_i w_i} \quad (5)$$

where \mathbf{u}_i is the unit vector associated with the i th component's direction, \mathbf{u}_i is the sum of all components in the \hat{i} th direction $\hat{i} = \arg \max_i w_i$, and \cdot denotes the inner product.

2.1.3. Control effort

The control effort is the energy that the loudspeaker array requires in order to achieve the reproduced sound field. It is defined as the total array energy (sum of squared source weights) relative to a single monopole q_r producing the same pressure in the target zone [14], and

expressed in decibels as

$$effort_A = 10 \log_{10} \left(\frac{\mathbf{q}^H \mathbf{q}}{q_r^H q_r} \right). \quad (6)$$

It is a necessity in any practical system to achieve a suitably low control effort. On the one hand, it is physically related to whether a set of source weights are realizable through real loudspeakers. Yet in addition, limiting the control effort results in there being less sound energy overall in the enclosure, leading to improved robustness to reflections in reverberant rooms, and limits the white noise gain of the system, improving robustness to other kinds of errors such as measurement noise.

2.2. Existing approaches

To facilitate a comparison between the proposed cost function and existing sound field control methods, ACC, PM and their hybrid are formally introduced in the following sections.

2.2.1. Acoustic contrast control

The ACC cost function [9], where the ratio of the spatially averaged sound pressure levels between the bright zone and the dark zone is maximized, represents the energy cancellation approach. Introducing the indirect Tikhonov regularization proposed by Elliot *et al.* [15], the cost function is written as a constrained optimization problem based on minimizing the dark zone pressure and constrained by the bright zone pressure and control effort:

$$J = \mathbf{p}_d^H \mathbf{p}_d + \lambda_1 (\mathbf{p}_b^H \mathbf{p}_b - B) + \lambda_2 (\mathbf{q}^H \mathbf{q} - E), \quad (7)$$

where the subscripts \cdot_d and \cdot_b denote assignment of the pressure vectors with respect to the dark and bright (target) zones, respectively, B is the target sound pressure in the bright zone, and E is the maximum allowed control effort.

Taking the derivative of J and setting to zero, we obtain:

$$\frac{\delta J}{\delta \mathbf{q}} = 2 \left[\mathbf{G}_d^H \mathbf{G}_d \mathbf{q} + \lambda_1 \mathbf{G}_b^H \mathbf{G}_b \mathbf{q} + \lambda_2 \mathbf{q} \right] = 0, \quad (8)$$

which can be rearranged as an eigenvalue problem of the form $\lambda_1 \mathbf{q} = \mathbf{A}\mathbf{q}$:

$$\lambda_1 \mathbf{q} = -(\mathbf{G}_b^H \mathbf{G}_b)^{-1} (\mathbf{G}_d^H \mathbf{G}_d + \lambda_2 \mathbf{I}) \mathbf{q}, \quad (9)$$

where \mathbf{I} is the identity matrix. The minimum can be found by taking the eigenvector corresponding to the

minimum eigenvalue of $(\mathbf{G}_b^H \mathbf{G}_b)^{-1} (\mathbf{G}_d^H \mathbf{G}_d + \lambda_2 \mathbf{I})$, which is equivalent to taking the eigenvector corresponding to the maximum eigenvalue of $(\mathbf{G}_d^H \mathbf{G}_d + \lambda_2 \mathbf{I})^{-1} (\mathbf{G}_b^H \mathbf{G}_b)$ [15]. The regularization term λ_2 therefore regularizes both the control effort and the numerical conditioning of the inversion of $\mathbf{G}_d^H \mathbf{G}_d$. In order to ensure the latter over all frequencies, the regularization parameter is split such that $\lambda_2 = \lambda_{min} + \lambda_{eff}$, where λ_{min} is first set to ensure that the condition number of $(\mathbf{G}_d^H \mathbf{G}_d + \lambda_2 \mathbf{I})$ is suitably controlled to avoid numerical errors and λ_{eff} is subsequently adjusted, if necessary, to ensure that E does not exceed the specified value.

2.2.2. Pressure matching

As a sound field synthesis method, any phase distribution can be specified for PM. A complex pressure is specified at each microphone; in this case, a plane wave is specified propagating through the target zone, and a pressure amplitude of zero is specified for the dark zone positions. The optimization cost function is written to minimize the error $\mathbf{e} = \mathbf{G}\mathbf{q} - \mathbf{d}$ between the desired sound field \mathbf{d} and reproduced sound field, with a control effort constraint for Tikhonov regularization:

$$J = \mathbf{e}^H \mathbf{e} + \lambda (\mathbf{q}^H \mathbf{q} - E). \quad (10)$$

The solution can then be found for the optimal \mathbf{q} :

$$\mathbf{q} = (\mathbf{G}^H \mathbf{G} + \lambda \mathbf{I})^{-1} \mathbf{G}^H \mathbf{d}, \quad (11)$$

where $\mathbf{G} = [\mathbf{G}_A \mathbf{G}_B]^T$ is the complete system plant matrix and $\lambda = \lambda_{min} + \lambda_{eff}$ is split as above.

2.2.3. PM and ACC hybrid

For the hybrid solution combining PM and ACC [21], the PM portion of the cost function is restricted to the reproduction of the bright zone, whilst the contrast control formulation is used for cancellation. Here, for consistency with the other methods, we introduce Tikhonov regularization instead of using the pseudo-inverse as in the original work:

$$J = \alpha \mathbf{p}_d^H \mathbf{p}_d + (1 - \alpha) \mathbf{e}_b^H \mathbf{e}_b + \lambda (\mathbf{q}^H \mathbf{q} - E), \quad (12)$$

where the error $\mathbf{e}_b = \mathbf{G}_b \mathbf{q} - \mathbf{d}_b$ is now between the desired sound field and the reproduced field in the target zone only. The weighting α provides a tuning parameter between the pure ACC solution and the pure target PM solution, with the standard pressure matching approach (Eq. (10)) being equivalent to $\alpha = 0.5$ [21]. The solution

can be determined by finding the gradient of Eq. (12) and rearranging for the source weights:

$$\mathbf{q} = \left[\alpha \mathbf{G}_d^H \mathbf{G}_d + (1 - \alpha) \mathbf{G}_b^H \mathbf{G}_b + \lambda \mathbf{I} \right]^{-1} (1 - \alpha) \mathbf{G}_b^H \mathbf{d}_b, \quad (13)$$

and as above, $\lambda = \lambda_{min} + \lambda_{eff}$.

3. PLANARITY CONTROL OPTIMIZATION

The proposed cost function optimizes the acoustic planarity by modification of the ACC cost function stated in Eq. (7). The elements of \mathbf{H} from Eq. (4) can be written in full, with respect to the microphones in the target zone, as

$$\mathbf{H}_b = \begin{pmatrix} h_{11} & h_{12} & \dots & h_{1M} \\ h_{21} & h_{22} & \dots & h_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ h_{I1} & h_{I2} & \dots & h_{IM} \end{pmatrix}, \quad (14)$$

where h_{im} is the steering vector between the i th incident angle with respect to the m th microphone in the zone. Using the super-directive (ACC) beamforming approach, \mathbf{H}_b can be determined for each steering angle by grouping the plane wave components c in each direction (based on the plane wave Green's function, $g_{i,c} = e^{jkr_c \cdot \mathbf{u}_i} / M$) in to a passband \mathbf{P} and stopband \mathbf{S} :

$$\begin{aligned} \mathbf{P}_i &= \{g_{p,c}\} \\ \mathbf{S}_i &= \{g_{s,c}\}, \end{aligned} \quad (15)$$

where p denotes passband range centered upon the i th angle and d denotes the stopband range. We can then populate the i th row of \mathbf{H}_b with \mathbf{h}_i , the eigenvector corresponding to the maximum eigenvalue of $(\mathbf{S}_i^H \mathbf{S}_i + \beta \mathbf{I})^{-1} \mathbf{P}_i^H \mathbf{P}_i$, at each steering angle, where $\beta = 10^{-4}$ is the regularization parameter.

\mathbf{H}_b represents a mapping between the complex pressures at the microphones and the reproduced plane wave energy distribution over azimuth, as previously introduced in Eq. (4). Therefore, it presents us with an opportunity to include it in the cost function for the sound zone optimization, and achieve some control of the plane wave energy in the target zone. In order to do this, a weighting must be applied based on the acceptable range of incoming plane wave directions. Such a weighting can be specified in terms of the desired normalized energy distribution over DOA by means of a diagonal matrix $\mathbf{\Gamma}$

comprising weights between zero and one:

$$\mathbf{\Gamma} = \begin{pmatrix} \gamma_1 & 0 & \dots & 0 \\ 0 & \gamma_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \gamma_l \end{pmatrix}, \quad (16)$$

where γ_i is the weighting applied for the i th steering angle.

The planarity optimization cost function can now be introduced:

$$J = \mathbf{p}_d^H \mathbf{p}_d + \lambda_1 (\mathbf{p}_b^H \mathbf{H}_b^H \mathbf{\Gamma} \mathbf{H}_b \mathbf{p}_b - B) + \lambda_2 (\mathbf{q}^H \mathbf{q} - E), \quad (17)$$

and deriving the solution in the identical manner to Eqs. (7 - 9) above, the optimal source weights can be found to be the eigenvector corresponding to the maximum eigenvalue of $(\mathbf{G}_d^H \mathbf{G}_d + \lambda_2 \mathbf{I})^{-1} (\mathbf{G}_b^H \mathbf{H}_b^H \mathbf{\Gamma} \mathbf{H}_b \mathbf{G}_b)$.

The optimization is thus constrained to maximize the sound energy in the target zone from among the potential incoming azimuths allowed by $\mathbf{\Gamma}$. The selection of $\mathbf{\Gamma}$ is clearly a significant factor. If the diagonal is filled with ones, then the cost function in Eq. (17) is no different from the contrast control formulation in Eq. (7) and identical performance is achieved. If, on the other hand, the vector is populated with zeros apart from a single target direction, a plane wave impinging from the specified direction should be reproduced. The approach is somewhat similar to that employed in [25], where a mapping matrix was used to deactivate certain loudspeakers for efficient 3-D reproduction based on a non-uniform array, yet here the loudspeakers are not expressly deactivated as they may contribute to the cancellation region as well as the target plane wave direction. Nevertheless, the solution is highly efficient. When the range of allowable angles is suitably designed, the system is free to maximize the energy under this constraint, which is best achieved by the generation of a planar sound field, and thus the planarity is optimized. Furthermore, if $\mathbf{\Gamma}$ is kept identical over frequency, similarity between adjacent frequency bins can be achieved.

4. SIMULATIONS

The operation and performance of the planarity optimization algorithm is demonstrated in the following by means of simulations.

4.1. Method

The simulations were conducted in Matlab, simulating a free-field lossless anechoic environment, with each

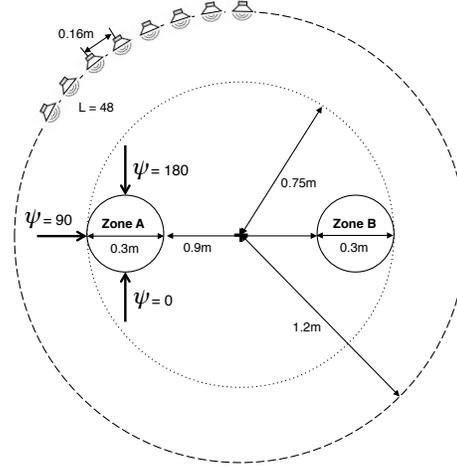


Fig. 1: Geometry of the sound zone system, where zone A is the target zone and zone B is the dark zone. The outer (dashed) circle represents the loudspeaker array, and the inner circle the reproduction radius with respect to the aliasing limit of the synthesis methods. The directions of plane wave incidence with respect to zone A are indicated.

source modeled as an ideal monopole. The free-field Green's function was used to populate the plant matrices, giving the transfer function at each microphone due to a loudspeaker at distance r :

$$g = \frac{j\rho c k q}{4\pi r} e^{jkr}, \quad (18)$$

where $\rho = 1.21 \text{ kg/m}^3$, $c = 342 \text{ m/s}$, and k is the wavenumber ω/c .

The test geometry comprised a circular array with 48 equally spaced loudspeakers, of radius 1.2m (see Fig. 1), and 156 omnidirectional microphones in each zone spaced at 2.1cm and arranged to sample 30cm diameter circles. The microphones used for calculating the sound zone filters (setup) and those for obtaining predictions (playback) were kept spatially distinct or mismatched [26] in order to assess the sound field in the zones without undue bias of the control points (which become more independent with increasing frequency). The target sound pressure level was set to 76dB SPL (achieved by scaling the prototype source weight vector \mathbf{q}), which has been shown to be a comfortable listening level and has been used during listening tests based on the sound zone interference situation [27]. This imposes

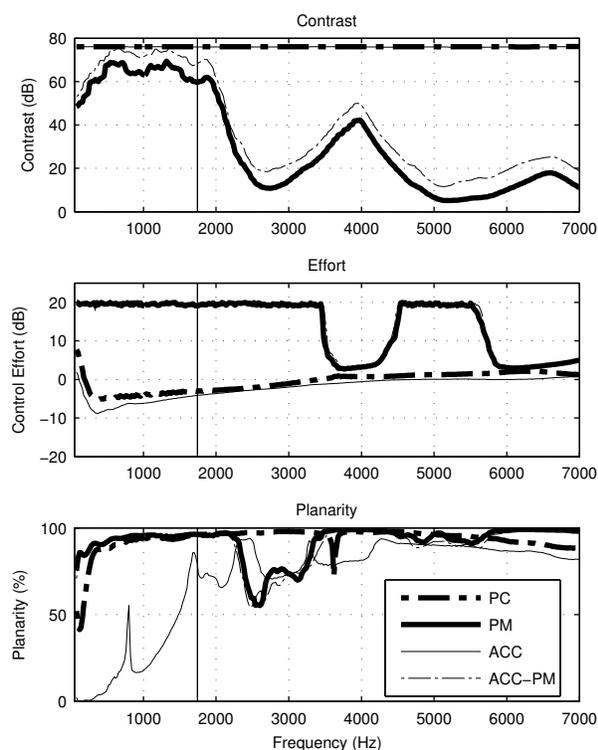


Fig. 2: Performance of planarity control (PC) with respect to ACC, PM and ACC-PM ($\alpha = 0.9$), under the metrics of contrast (top), effort (middle) and planarity (bottom). The aliasing limit imposed by the loudspeaker spacing is indicated.

an upper limit on the achievable contrast scores as we do not allow sound pressure levels below 0dB, although we consider 0dB to be measurable (there is no noise floor imposed).

To set the regularization conditions, the minimum regularization parameter component λ_{min} was set to enforce a maximum matrix condition number of 10^{10} , and the effort regularization parameter component λ_{eff} adjusted, where necessary, to enforce a maximum effort of 20dB, with reference to a single monopole on the radius of the circle (q_r , Eq. (6)).

The plane wave for the PM and ACC-PM hybrid (herein simply referred to as ACC-PM) approaches was specified to travel from north to south ($\psi = 180^\circ$, marked on Fig. 1), and the weighting matrix Γ was set to constrain the incoming plane wave components between 120° and

240° . The weighting on the diagonal of Γ is indicated in Fig. 4 (top). The weighting α for ACC-PM was set to 0.9 to encourage good contrast performance.

4.2. Planarity optimization performance

The planarity control (PC) method was applied to the array and the results obtained under the evaluation metrics introduced in section 2.1. Figure 2 shows the method's performance over frequency, alongside those obtained for ACC, PM and ACC-PM under the same conditions.

The PC contrast performance is very good and very consistent across the extended midrange band of 50-7000Hz. The term responsible for cancellation in the proposed planarity control (Eq. (17)) is unchanged from that in the ACC cost function (Eq. (7)) and the dark zone creation is therefore similar in each case, resulting in maximum cancellation as for ACC, and outperforming PM and ACC-PM.

Likewise, the control effort performance tends towards that of ACC, which gives preferable performance by a small margin across the whole range, outperforming the planarity control by up to 6dB at the lowest frequencies but generally being within 3dB. Nonetheless, the effort is below 0dB for much of the frequency range, and it is consistently preferable to PM and ACC-PM under the same conditions.

Finally, there is a good planarity performance across frequency. Under this metric, the synthesis metrics PM and ACC-PM naturally produce optimal scores for significant portions of the frequency range. However, with the exception of the low frequency performance (due to poor resolution of the planarity steering matrix in this region) and a narrow notch at 3.6kHz, the planarity scores are similar to PM and ACC-PM, and greatly improved from ACC, as the DOA constraint has removed the self-cancellation artifacts from the reproduced sound field.

Perhaps the most striking characteristic of the planarity control method is its robustness as a function of frequency. Where PM and ACC-PM suffer from well documented limitations to the upper frequency of accurate reproduction, depending on the loudspeaker spacing and array radius (see e.g. [19]), the planarity control is able to operate well above this limit. In fact, the problems above the aliasing limit (1.74kHz as marked on Fig. 2) for PM and ACC-PM can be observed in relation to each of the evaluation metrics: from the contrast the effect of aliasing lobes passing through the dark zone can be observed, and the corresponding control effort response noted. The

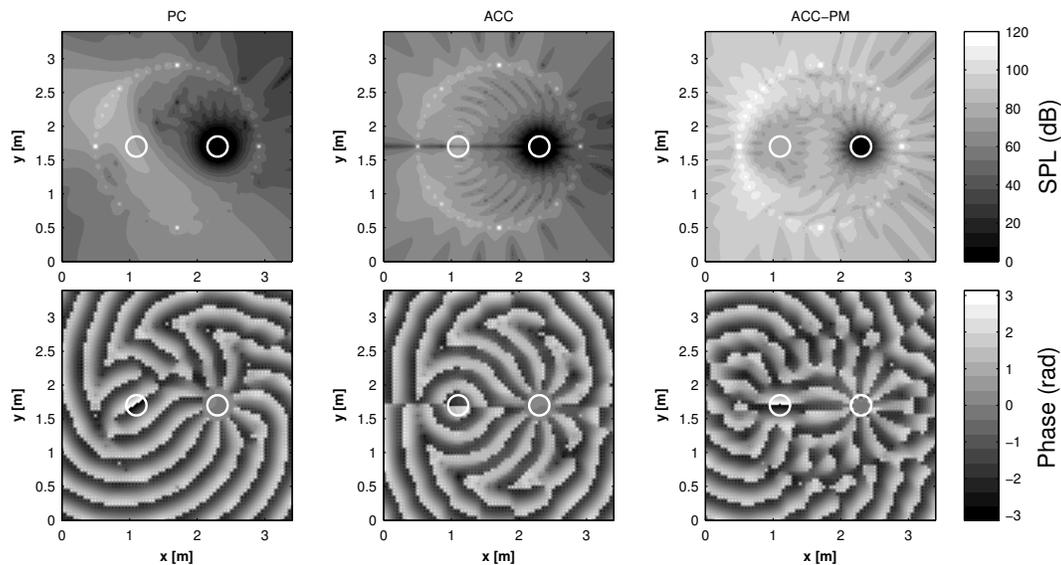


Fig. 3: Sound pressure level (top row) and phase (bottom row) maps for PC, ACC and ACC-PM ($\alpha = 0.9$). The target (left) and dark zones are indicated by the white circles. For the sound pressure level maps, white indicates a high sound pressure and black a low sound pressure

planarity response is interesting at high frequencies for PM and ACC-PM, because a planar target field is still reproduced. As there is little to distinguish between the performance characteristics of PM and ACC-PM apart from the slight improvement in contrast, ACC-PM is taken forward for further simulations.

The optimal contrast and planarity performance obtained using planarity control can be further clarified by studying the sound pressure level and phase maps shown in Fig. 3. We can now confirm that the planarity control produces an ACC-like dark zone, yet replaces the north-south standing wave (visible across the whole of the bottom-middle plot) in the target zone with a planar field (indicated by the sharp transition in the phase response), and reduces the overall sound pressure in the enclosure as a consequence of the low effort score with relation to PM and ACC-PM (visible by comparing the amount of bright white in the top row of Fig. 3).

4.3. Target sound field properties

The properties of the sound field reproduced by the planarity control method are of some interest to potential users. First, we consider the energy distribution over azimuth (with respect to the target zone) obtained for the

window function used for the simulations in section 4.2. We have seen from the planarity scores (Fig. 2, bottom) and the phase distributions in the enclosure (Fig. 3, bottom) that the planarity control method is capable of creating highly planar fields in the target zone, for single frequencies. However, these plots do not give us an indication of the range of incoming plane wave directions as a function of frequency. Therefore, in Fig. 4 the normalized energy distributions for multiple frequencies have been plotted across azimuth for planarity control, ACC and ACC-PM. The energy over azimuth is estimated using the same beamforming approach introduced in section 3. This gives us a useful insight into the planarity control's performance in relation to the existing methods. The synthesis adopted in ACC-PM can be seen to successfully place the plane wave propagation to the specified direction, with a wider lobe at low frequency due to the poor beamformer resolution (c.f. planarity scores for PM at low frequency in Fig. 2), and the higher frequency aliasing effects due to the source array noticeable as side lobes. Conversely, ACC produces plane wave energy from a wide range of azimuths as well as self-cancellation patterns. It is likely that such a field would result in an unpleasant listening experience. The distribution of plane wave energy directions over frequency

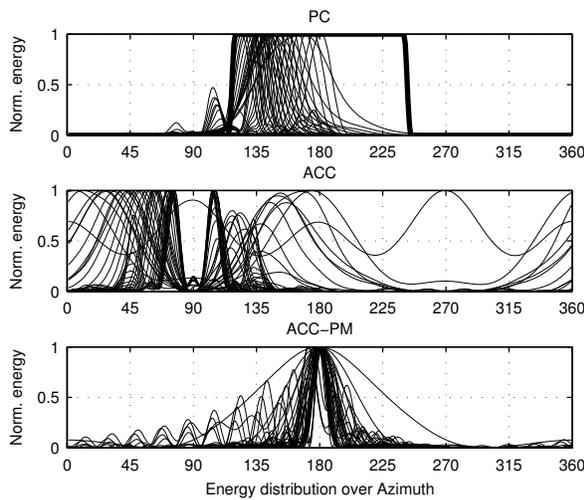


Fig. 4: Energy distributions over azimuth for PC (top), ACC (middle) and ACC-PM (bottom), plotted at 100Hz intervals from 100-7000Hz. The bold line in the uppermost plot indicates the specified window along the diagonal of Γ , and the directions 90° and 180° correspond to incoming plane wave directions of west-east and north-south, respectively, in relation to Fig. 3.

for planarity control can be noted to conform, for the most part, to the target range, with side lobes emerging at higher frequencies above the array aliasing limit.

To test the ability of the planarity control to reproduce a specific incoming plane wave direction, the window was set to allow a single azimuth (with a raised-cosine weighting to smooth the transition), and the direction varied. Three significant results are plotted in Fig. 5 for specified directions of 90° , 146° (the optimal case for this frequency) and 180° , at 1kHz, with PM also included as a reference. In the middle plot (180°), the planarity control method can be seen to accurately place the plane wave to arrive from the required direction (corresponding to north-south in Fig. 3), and for the optimal case this is achieved with additional side lobe suppression, although the width of the energy lobe for PM is slightly narrower. Yet for directions perpendicular to this (west-east propagation shown), which would require a beam to be placed across the dark zone, a highly self-cancelling pattern is instead reproduced and the peak in this direction is unsatisfactory. There is no variation in the contrast between these cases and the effort difference is minimal, yet if PM had been applied, the cancellation would have

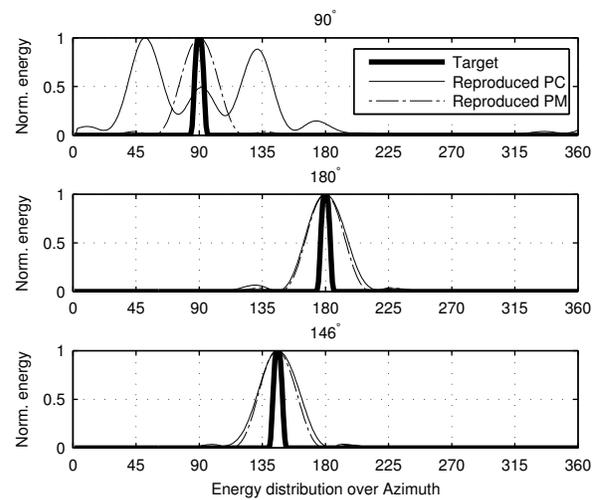


Fig. 5: Target (bold) vs. achieved energy distribution over azimuth at 1kHz, using planarity control to specify the DOA, for 90° (west-east) (top), 180° (north-south) (middle) and 146° (optimal) (bottom). Maximum contrast is achieved in each case. Energy reproduced by PM is included for reference (dot-dash line).

been poor and the effort very high, albeit with the specified plane wave component reproduced. An interesting property of the planarity control cost function is therefore exposed: that producing high contrast is the priority of the optimization, and that where specification of the incident direction does not conflict with contrast performance, the energy can be placed precisely in the desired direction.

The behavior over frequency for a constrained window ($146^\circ \pm 20^\circ$ with a raised cosine weighting) is clarified by Fig. 6. At low frequencies, the compounding of poor beamformer resolution for both setup and evaluation results in very wide lobes, at mid frequencies up to the spatial aliasing limit the placement is satisfactory, and at high frequencies the behavior is rather similar to that of ACC-PM, where some side lobes emerge. Even so, the main energy components remain close to the specified window and good contrast and planarity are still achieved.

5. CONCLUSIONS

A method for optimizing the planarity in the target zone, as well as producing significant cancellation between zones, has been proposed. The method has been shown

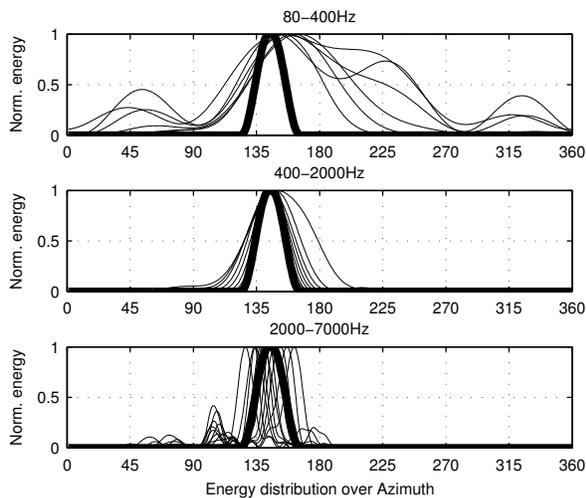


Fig. 6: Target (bold) vs. achieved energy distributions over azimuth with lines plotted over frequency, for low (top), mid (middle) and high (bottom) frequency bands, using planarity control to constrain the DOA to a window around the optimal angle of 146° . Maximum contrast is achieved in each case.

to be comparable to the well established acoustic control method in terms of contrast and control effort, and superior for creating a planar field in the target zone. It also outperforms the pressure matching approach and a state of the art hybrid between pressure matching and acoustic contrast control, particularly in terms of its ability to produce a good cancellation region above the spatial aliasing region, and a planar field around this limit. The resolution of the microphone array beamformer limits planarity performance at low frequencies, below 400Hz. Definition of the weighting matrix is very important for good performance. The ability of planarity control to constrain incident plane wave directions over frequency has been demonstrated, and furthermore under the condition that it does not require propagation across the dark zone, a precise plane wave direction can be specified. The method therefore presents a compelling cost function for sound zones where the self cancellation artifacts of energy cancellation approaches can be reduced whilst allowing more flexibility over the incident plane wave specification, yet with the potential to reproduce a wave from a single direction if required.

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