Audio Engineering Society

Convention Paper

Presented at the 130th Convention
2011 May 13–16 London, UK

Design of a Compact Cylindrical Loudspeaker Array for Spatial Sound Reproduction

Mihailo Kolundžija[1], Christof Faller[1], and Martin Vetterli[1][2]

[1]*Audiovisual Communications Laboratory, Ecole Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland*

[2]*Department of EECS, University of California at Berkeley, Berkeley CA 94720, USA*

Correspondence should be addressed to Mihailo Kolundžija (`mihailo.kolundzija@epfl.ch`)

ABSTRACT

Building acoustic beamformers is a problem whose solution is hindered by the wide-band nature of audible sound. In order to achieve a consistent directional response over a wide range of frequencies, a conventional acoustic beamformer needs a high number of discrete loudspeakers and be large enough to achieve a desired low-frequency performance. The acoustic beamformer design described in this paper uses measurement-based optimized beamforming for loudspeakers mounted on a rigid cylindrical baffle. Super-directional beamforming enables achieving desired directivity with multiple loudspeakers at low frequencies. High frequencies are reproduced with a single loudspeaker, whose highly directional reproduction—due to the cylindrical baffle—matches the design goals. In addition to the beamformer filter design procedure, it is shown how such loudspeaker array can be used for spatial sound reproduction.

1. INTRODUCTION

In applications such as public address (PA) system design, reverberation reduction, or surround sound reproduction, one is faced with a challenge of designing a loudspeaker system that reproduces sound towards a desired direction and keeps the energy of the sound emitted towards other directions low. In some of the applications, the mentioned directional playback needs to be consistent over a wide range of audible frequencies.

Various designs have addressed the problem of directional sound playback. Roughly speaking, there are three types of directive loudspeakers: flat panel loudspeakers, whose large flat membrane acts as a plane source and emits the sound mostly towards the front; ultrasound-based flat loudspeaker panels which use beamforming in the ultrasound frequency range and demodulate the sound to the audible range thanks to the non-linearity in the air (e.g., see [1, 2]); and loudspeaker arrays, which use beamforming techniques [3], usually combining different loudspeakers in different frequency ranges to achieve approximately constant wide-band directivity (e.g., see [4]). The problems of the first two designs are low dynamic range and limited sound reproduction quality. Loudspeaker arrays, on the other hand, need to be large and contain many elements to achieve consistent behavior both at low and high frequencies.

We describe a design of baffled loudspeaker arrays which are consistently directive over a wide range of frequencies. Our procedure is based on super-directional beamforming techniques [5] at low frequencies, and single-loudspeaker playback at high frequencies. Super-directional techniques are very powerful at designing high-directivity beamformers, but they only work at low frequencies, where the sound wavelength is much shorter than the distance between loudspeakers. To complement the super-directional beamforming, the design uses a rigid baffle, which endows loudspeakers with slowly-changing, highly directional high-frequency response, which can be matched by the low-frequency response obtained with super-directional beamforming.

Before going into more detail on loudspeaker array design, we list relevant design goals which our procedure needs to address.

- **High directivity**
  The main goal of our loudspeaker array design is highly directional reproduction of sound. Additionally, high directivity should be kept over a wide frequency range, such that the desired spatial effects are as frequency-invariant as possible.

- **Steering capability**
  Not only are we interested in being able to reproduce sound directionally, but also to do so towards a number of different directions. This property is highly desirable for PA systems or surround reproduction in rooms.

- **Compact size**
  Although not a primary goal, having a compact loudspeaker array with only a few loudspeakers is advantageous for a number of reasons, both from the users' and designers' perspective (e.g., saving listening room space and cost).

- **Measurement-based design**
  Sound scattering and propagation properties on symmetric geometries are well analyzed and understood, but models are often not sufficient for practical system design. There is a number of reasons for discrepancies between a model and a real system. These include manufacturing inaccuracies, model simplifications, equipment miscalibration etc. In order to avoid the mentioned sources of errors, we rely on measurements of the loudspeaker array in a number of control points such that manufacturing inaccuracies and miscalibration are accounted for.

The paper is organized as follows. Section 2 analyzes the theoretical model of sound radiation from a loudspeaker mounted on a rigid cylinder and motivates the baffled loudspeaker array design. Section 3 describes different aspects of designing optimized beamforming filters for a directional loudspeaker array. Design of a beamformer using a simulated baffled loudspeaker model is presented in Section 4. A prototype array and its performance are described in Section 5. Section 6 describes how a directional loudspeaker array can be used for reproducing spatial sound. Conclusions are given in Section 7.

2. ACOUSTICAL DESIGN

It is well known that baffled loudspeakers have frequency-dependent directivity. At low frequencies, they act approximately as an omnidirectional radiator, emitting sound almost equally in all directions. As the frequency increases towards the high end of the audible sound spectrum, they become increasingly directional, emitting most of the sound energy towards the front of the loudspeaker axis.

The observation, used later as one of the cornerstones of the proposed beamformer design, is that at high frequencies, a baffled loudspeaker has a directivity which does not change substantially as the frequency increases. In other words, starting from an omnidirectional radiation pattern at very low frequencies, the directivity pattern of a baffled loudspeaker changes notably up to a certain frequency

f_0, above which the directivity pattern does not exhibit big variations over a wide range of frequencies.

2.1. Baffled loudspeaker model

To support the claim about "bi-modality" of the baffled loudspeaker's directivity, we show an example involving a model of a baffled piston loudspeaker. The model involves an infinite cylindrical baffle of radius a and a vibrating piston of length $2L$ and circumferential width $2\alpha a$. Fig. 1 illustrates the geometry of the model.

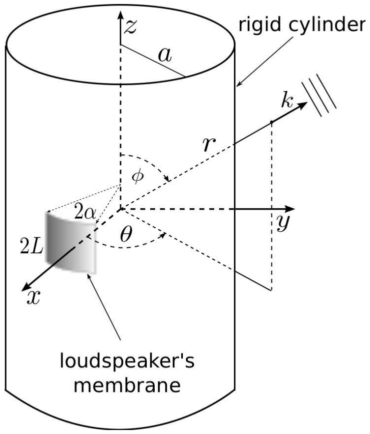

Fig. 1: *Model of a piston loudspeaker mounted on an infinite rigid cylindrical baffle.*

This simplifying baffled loudspeaker model is convenient to illustrate the concept, as it possesses a closed-form analytical solution which readily serves for analysis. The far-field sound field radiated from a vibrating piston mounted on an infinite cylindrical baffle is given by [6]:

$$p(\omega,r,\theta,\phi) \approx C(\omega,r,\theta)e^{ikr}\sum_{n=-\infty}^{\infty}\frac{(-i)^n e^{in\phi}\mathrm{sinc}(n\alpha)}{H_n'(ka\sin\theta)} \tag{1}$$

with

$$C(\omega,r,\theta) = \frac{4b\alpha L\rho_0 c}{2\pi^2}\frac{\mathrm{sinc}(kL\cos\theta)}{r\sin\theta}, \tag{2}$$

where r, θ, and ϕ are the standard spherical coordinates depicted in Fig. 1, ρ_0 is the density of air, c the speed of sound propagation, b the piston's velocity, $k=\omega/c$ the wave number, and $H_n'(x)$ the first derivative of the Hankel's function of the first kind. In the following analysis, the piston will have sides of equal length, $L=a\alpha$.

Although the far-field response is not easy to predict from Eq. (1), it can be predicted that:

- High-frequency directivity grows inversely with piston's size $2a\alpha$[1] for a fixed baffle radius a
- High-frequency directivity grows with the baffle radius a, for a constant piston size.

To confirm the above claims, we illustrate normalized frequency-dependent directional responses of the considered baffled loudspeaker model. Fig. 2 illustrates the influence of the piston's size, whereas Fig. 3 shows the influence of the size of the baffle. Note that the polar diagrams are a bit unusual, as they show normalized directional responses clipped at a threshold value of -15 dB. The reason is to reveal the dependence of the high-frequency directivity on the two considered system parameters—piston's and baffle's size, where the directivity is related to the directional response's -15 dB level. The directional response below the chosen threshold, although more varying, is low enough to be considered less relevant.

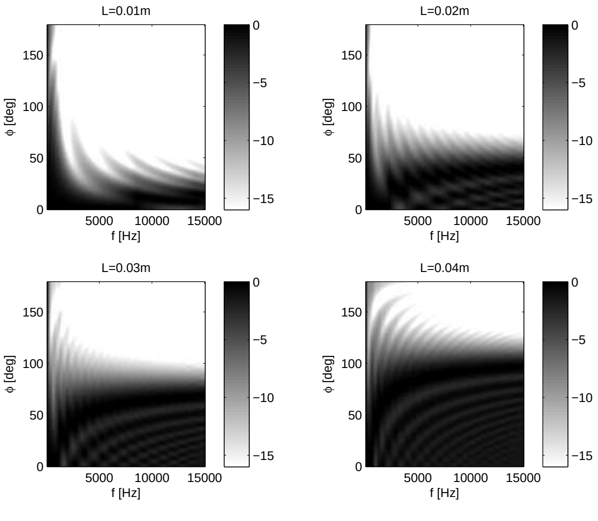

Fig. 2: *Frequency-dependent normalized directional responses of cylindrically baffled vibrating piston, clipped at -15 dB. The piston side lengths $2a\alpha$ (equal to L) are varied, while the baffle radius is kept constant at $a=0.2$ m.*

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[1] We consider equal-side pistons, i.e., $a\alpha = L$.

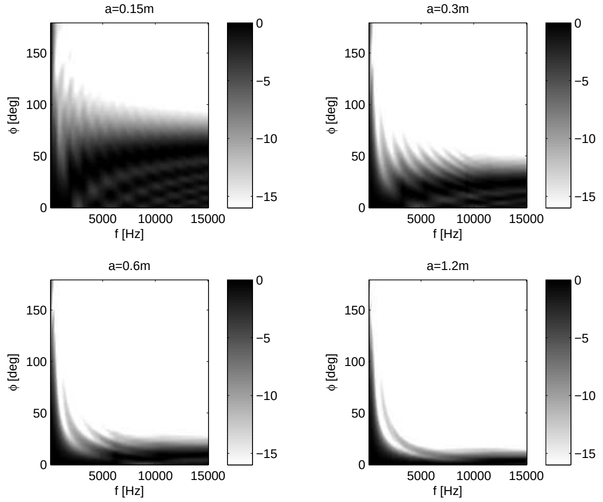

Fig. 3: *Frequency-dependent normalized directional responses of cylindrically baffled vibrating piston, clipped at* -15 *dB. The piston size lengths are kept constant at* $2a\alpha = L = 2$ *cm, while the radius* a *is varied.*

From Fig. 2 and 3, we can see that the directivity of a cylindrically baffled piston is inversely proportional to the piston's dimension $a\alpha$ and directly proportional to the baffle's radius a. Furthermore, as a guide for choosing the dimensions of a piston and a baffle, one can use the observation that the -15 dB threshold appears around the angle $\phi_T = \frac{\pi}{3}$ off the piston's axis when the piston covers the circumferential angle of $2\alpha = 0.2$ rad.

Note, however, that the pressure in (1) is approximately proportional to piston's area at low frequencies. Thus, even though smaller pistons can be used to increase loudspeaker's directivity, their size can not be made too small, as it may violate design goals for achievable sound pressure levels (SPL) at low frequencies.

Fig. 2 and 3 also confirm the claim of a roughly bi-modal behavior of baffled loudspeaker's directional responses. Low frequencies, up to a few kHz,[2] are characterized by a sharp transition from an omni-directional to a directional pattern. High frequencies, starting from a few kHz, are characterized by directional responses that have little variation with frequency.[3]

3. BEAMFORMER DESIGN

From the previous section, we have seen that an adequately sized baffled loudspeaker design can provide a desired directivity at high frequencies. In order to maintain that behavior down to low frequencies, one needs to combine multiple loudspeakers and use beamforming.

Additionally, although the sound scattering from cylindrical baffles is used as a starting point for loudspeaker array and analysis, we do not rely on it explicitly in the beamformer design procedure. Neither do we rely on the geometry of the array. Similarly, we do not require the control points to be very precisely placed and lie exactly on a circle centered at the array's center, which is a usual requirement of modal beamforming techniques.

Our beamformer design is fully based on measurement of the array. It relies on the above mentioned bi-modal nature of directional response of a baffled loudspeaker, and that a single (front) loudspeaker can drive the high frequencies alone. Additionally, the beamformer design relies on essential angular band-limitedness of the directional response for choosing the number of control points that avoids large errors due to aliasing.

3.1. Filter design procedure

We use a baffled circular loudspeaker array with L loudspeakers, illustrated in Fig. 4. The loudspeaker array's look direction[4] coincides with the look direction of one loudspeaker, which we denote the *main loudspeaker*. Without loss of generality, we assign index 1 to the main loudspeaker.

Each loudspeaker's response is measured in M control points covering a circle of radius r centered at the array's center. Measurements are done in free-field or anechoic conditions. Additionally, without sacrificing generality, we assign index 1 to the control point lying in the loudspeaker array's look direction.[5]

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[2] The "border frequency" between the two modes depends on the baffle's and piston's dimensions.

[3] Responses at rear angles are more varying, but they are highly attenuated such that their variability is of little significance for the considered applications.

[4] We will use *on-axis* and *look direction* interchangeably throughout the rest of the paper.

[5] The control point with index 1 is also in the look direction of the loudspeaker with index 1.

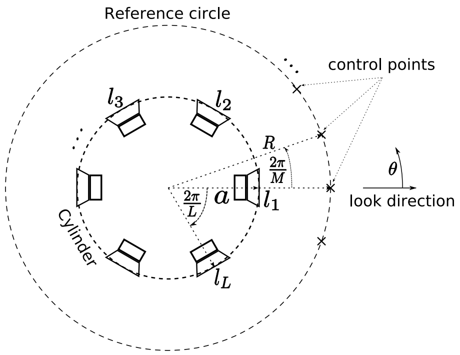

Fig. 4: *Circular loudspeaker array configuration and reference circle with control points.*

Let the matrix $\mathbf{G}(\omega)$ contain the filters $g_{ij}(\omega)$ representing the transmission path from the j-th loudspeaker to i-th measurement point. Note that each column $\boldsymbol{g}_i(\omega)$ of the matrix $\boldsymbol{G}_{ij}(\omega)$ contains the directional response of loudspeaker i at frequency ω. Further, let the vector $\mathbf{h}(\omega)$ contain the loudspeaker filters $h_i(\omega)$. In the following, unless necessary, we will use quantities without explicitly denoting their dependence on frequency ω.

Motivated by the previous observations, we take the directional response $\mathbf{g}_1(\omega_0)$ of the main loudspeaker at some high frequency ω_0 to be the desired directional response of the array. Additionally, while keeping the shape of the directional response (polar pattern) unchanged, we scale it with a frequency-dependent factor

$$s(\omega) = \frac{|g_{11}(\omega)|}{|g_{11}(\omega_0)|} ,$$

where $g_{11}(\omega)$ and $g_{11}(\omega_0)$ are the on-axis responses of the main loudspeaker at frequencies ω and ω_0, respectively. This makes the on-axis desired response of the entire array equal to the on-axis response of the main loudspeaker.[6] The frequency-dependent desired response is thus given by

$$\boldsymbol{d}(\omega) = s(\omega)\, \mathbf{g}_1(\omega_0) . \tag{3}$$

Above frequency ω_0, we avoid beamforming and use only the main loudspeaker.

The beamformer design can be expressed in the frequency domain as a constrained optimization problem the computes a vector $\boldsymbol{h}$ of loudspeaker filter complex gains, where the function being optimized is a norm of the error

$$\boldsymbol{e} = \boldsymbol{G}\boldsymbol{h} - \boldsymbol{d} \tag{4}$$

between the desired and obtained directional response over the control points, $\boldsymbol{d}$ and $\boldsymbol{G}\boldsymbol{h}$, respectively. But before we present the design procedure in detail, let us motivate and explain the modifications we made to the standard unconstrained minimum mean squared error (MMSE) design procedure [7].

Weighted error. Human auditory system is sensitive to relative changes of sound quantities, and frequency response irregularities are no exception [8]. Thus, in a scenario where a desired directional response is highly angle-varying, it is not reasonable to sum the beamformer response errors at control points equally. It is rather judicious to penalize the absolute error more at points where the desired response level is low, and less where it is high. Thus, we minimize the relative error at the control points

$$\boldsymbol{e}_w = \operatorname{diag}(|\boldsymbol{d}|)^{-1} \left(\boldsymbol{G}\boldsymbol{h} - \boldsymbol{d}\right) , \tag{5}$$

where $\operatorname{diag}(\boldsymbol{x})$ of a vector $\boldsymbol{x}$ denotes a square diagonal matrix whose main diagonal contains the elements of $\boldsymbol{x}$, and $|\boldsymbol{x}|$ denotes a vector containing absolute values of the elements of $\boldsymbol{x}$.

Robust design. We try to avoid driving any of the loudspeakers with large gain at any frequency. There is a number of reasons for such a design decision. First, driving loudspeakers with large gains to better match the desired pattern effectively decreases the dynamic range of the loudspeaker array. Second, the l_2 norm of the beamformer filters' impulse response is related to the beamformer's *white noise gain* [9]

$$\text{WNG} = \|\boldsymbol{h}\|^{-2} , \tag{6}$$

which quantifies its robustness. The larger the white noise gain, the less sensitive to random (measurement or placement) errors the designed beamformer. Thus, limiting the gains also helps increasing robustness.

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[6] The goal of the described procedure is not to equalize the on-axis frequency response of the main loudspeaker. This can be done separately, using conventional loudspeaker equalization approaches.

Favoring front loudspeaker. We have shown in Section 2 that high-frequency directional response of a baffled loudspeaker does not vary substantially with frequency. Thus, if the beamformer's desired response is set to the directional response of the front loudspeaker at some fixed high frequency ω_0, then it is to be expected that as the frequency approaches ω_0, the beamformer will tend to mostly use the main loudspeaker. As a consequence, the response of the beamformer will be dominated by the response of the main loudspeaker, both in terms of magnitude and in terms of phase.

In classical MMSE beamformer designs, error is taken as a complex number—accounting for both amplitude and phase errors—and its norm, being minimized, is computed over all control points. On the other hand, the focus of a beamformer is reproducing sound highly directionally, and phase errors are of little relevance. Since minimizing the norm of magnitude error makes the beamformer design a non-convex optimization problem, we use a heuristic that slightly modifies the error term without affecting the problem's convexity.

The heuristic relies on the high-frequency dominance of the main loudspeaker, and consists of aligning the phase of the desired response to the phase of the main loudspeaker [10],

$$\boldsymbol{d}_{pa} = \operatorname{diag}(|\boldsymbol{g}_1|)^{-1} \operatorname{diag}(\boldsymbol{g}_1)\, |\boldsymbol{d}| \,. \tag{7}$$

At low frequencies, phase differences between the responses of array's loudspeakers are small, and the impact of the phase correction is negligible. However, the phase correction improves the desired response synthesis at high frequencies [10]. It also enables a smooth transition between using all to using only the main loudspeaker, which is highly desirable when designing practical finite impulse response (FIR) filters.

Putting the above design decisions together, the beamformer design problem can be stated as follows:

$$\begin{array}{ll} \underset{\boldsymbol{h}}{\text{minimize}} & \|\operatorname{diag}(|\boldsymbol{d}'|)^{-1} (\boldsymbol{G}'\boldsymbol{h} - \boldsymbol{d}'_{pa})\|_x \\ \text{subject to} & |h_i| \leq h_{max}, \quad i = 1, \dots, L \\ & |\boldsymbol{r}_1^T \boldsymbol{h} - d_1| \leq t|d_1| \,, \end{array} \tag{8}$$

where $x \in \{2, \infty\}$ is the minimized relative error norm (Euclidean or min-max), $\boldsymbol{G}'$ is the matrix obtained by removing the first row of the matrix $\boldsymbol{G}$, $\boldsymbol{d}'$ and $\boldsymbol{d}'_{pa}$ are vectors obtained by removing the first element of the vectors $\boldsymbol{d}$ and $\boldsymbol{d}_{pa}$, respectively, $\boldsymbol{r}_1^T$ is the first row of the matrix $\boldsymbol{G}$, and t is a small constant used for controlling deviations of the on-axis frequency characteristic. If the on-axis frequency response of the beamformer needs to exactly match the desired one, the parameter t is to be set to zero.

4. SIMULATIONS

In order to assess the wide-band performance of the described beamformer, we simulated a model of a six-element loudspeaker array mounted on a cylindrical baffle. The vibrating pistons, modeling separate loudspeakers, were uniformly spaced on the baffle's circumference. The radius of the baffle was $a = 20$ cm, and the sides of pistons were $2L = 2a\alpha = 4$ cm.

The control points used for computing the loudspeaker filters were placed uniformly on a circle of radius $r = 3$ m centered at the array's center. The number of reference points, $M = 13$, was chosen based on the assumed effective angular smoothness of the loudspeakers' directional responses at low frequencies.

The desired directional response was taken to be the response of the main loudspeaker alone at frequency $f_0 = 4$ kHz, which is shown in Fig. 5.

Fig. 5 compares directional response of the beamformer to the desired response at a number of frequencies ranging from 300 Hz to 12 kHz. We can observe that there is a good match between the two at all frequencies, in the sense that deviations do not exceed a few decibels.

To better illustrate the consistency of the obtained directional response over frequencies, Fig. 6 shows frequency responses at various angles on the reference circle. We can see that there is no large deviations in the frequency response at most angles. More prominent variations of the frequency response happen at highly attenuated rear angles, but as mentioned earlier—variations at very low sound levels are not detrimental in the foreseen applications.

Fig. 7 shows the frequency responses of the computed beamformer filters. As expected from the beamformer design procedure, the front loudspeaker drives the high frequencies independently, and the

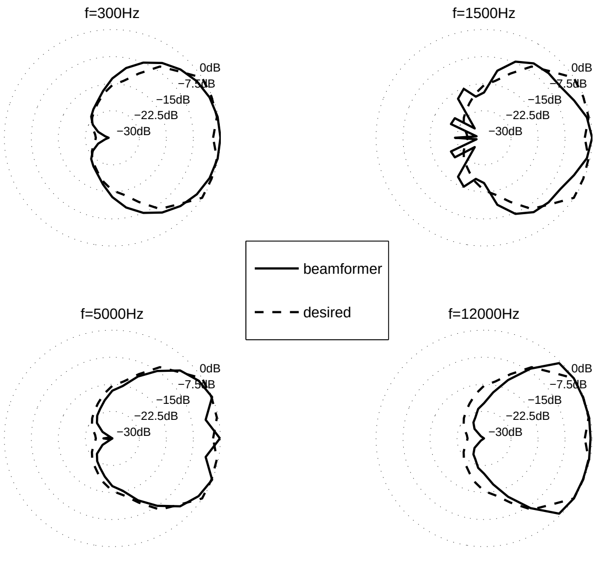

Fig. 5: *Loudspeaker array directional responses (in logarithmic scale) at various frequencies, on the reference circle of radius $r = 3$ m.*

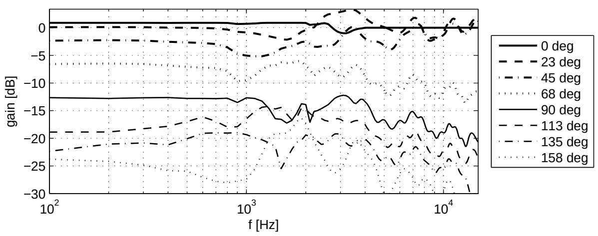

Fig. 6: *Loudspeaker array frequency responses at various angles on the reference circle of radius $r = 3$ m.*

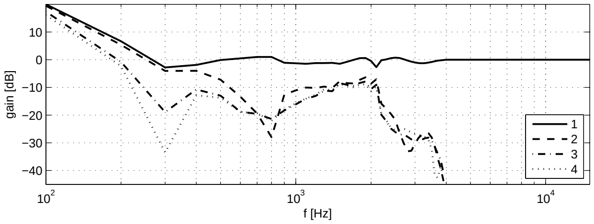

Fig. 7: *Loudspeaker array beamformer filters' frequency responses.*

other loudspeakers effectively help at low frequencies. Furthermore, we can see a desirable smooth transition between array beamforming and acoustical beamforming (provided by the baffle).

5. EXPERIMENTS

In addition to simulations, we tested the proposed approach to directional loudspeaker design in practice. We assembled a cylindrical array of six small Logitech Z4 loudspeakers, as illustrated in Fig. 8.

Fig. 8: *Prototype loudspeaker array consisting of six Logitech Z4 loudspeakers arranged as a cylinder having a radius $r \approx 8$ cm.*

As stated earlier, our beamformer design procedure is entirely based on measured loudspeaker responses, and not on a model. The measurement of the assembled loudspeaker array was made in an anechoic chamber. The loudspeaker array was fixed on a turntable and measured with a fixed omnidirectional microphone $r = 2$ m away from its center. The measurements of all loudspeakers were made at 13 turntable rotation steps of $\frac{2\pi}{13}$ radians, which is equivalent to measuring the array uniformly at 13 equidistant points on a circle of radius $r = 2$ m.

Measurements were done using swept sines, covering the frequency range from 300 Hz to 12 kHz. Due to limited access to measurement resources, the measurements were done only once, without averaging multiple responses.

Fig. 9 shows the frequency responses of one loudspeaker from the array at control points covering the angles in the range $[0, \pi]$. Fig. 10 shows the loudspeaker's directional responses at different frequencies. As expected, the directional response at high frequencies above 4 kHz is not highly varying with frequency. Also, the directivity at low frequencies, below 2.5 kHz, increases with frequency.

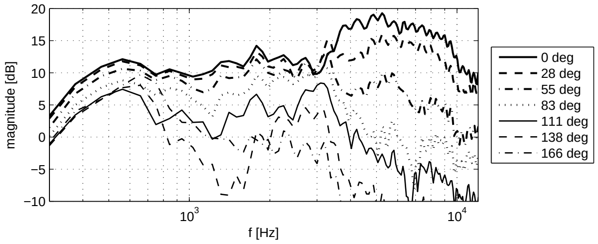

Fig. 9: *Measured frequency responses of one loudspeaker of the built loudspeaker array prototype. The diagram contains frequency responses at seven control points on the measurement circle of radius $r = 2$ m enclosing the array.*

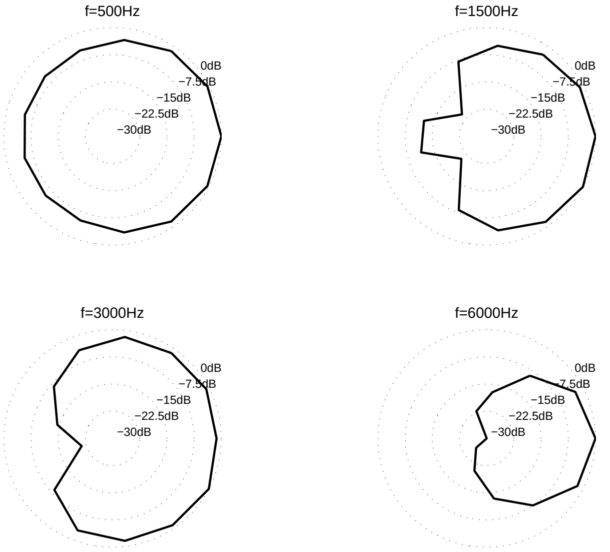

Fig. 10: *Measured directional responses of one loudspeaker of the built loudspeaker array prototype at different frequencies f. The diagram contains directional responses sampled at 13 control points on the measurement circle of radius $r = 2$ m enclosing the array.*

In the frequency range between 2.5 kHz and 4 kHz, the directional response becomes less directive. At frequencies around 3 kHz, the on-axis response is weaker than the responses at angles up to 90° off the look direction. Additionally, the responses towards side and rear directions are much less attenuated than at low and high frequencies. This mid-frequency behavior is the only example where a practical loudspeaker behavior substantially deviates from the simplified theoretical model, analyzed in Section 2.

To compute the beamformer filters, we specified as desired the directional response of the front loudspeaker at frequency $f_0 = 5$ kHz. The frequency $f_0 = 5$ kHz is also the frequency above which only the front loudspeaker is used for sound reproduction. We allowed the on-axis frequency response of the array to deviate by $t = 1$ dB from the on-axis frequency response of the front loudspeaker.

The frequency responses of the beamformer at the control points belonging to the first two quadrants are shown in Fig. 11.[7] The frequency responses at different control points—except for the rear, highly attenuated directions—do not vary substantially at low frequencies up to 2 kHz, and at high frequencies, above 4 kHz. However, we were not able to achieve the desired directional response in the frequency range $2-4$ kHz. Frequency responses at side directions have a high peak in this frequency range, which can manifest itself as an audible coloration [8]. Fig. 12 illustrate the described frequency-dependent behavior, only using polar plots.

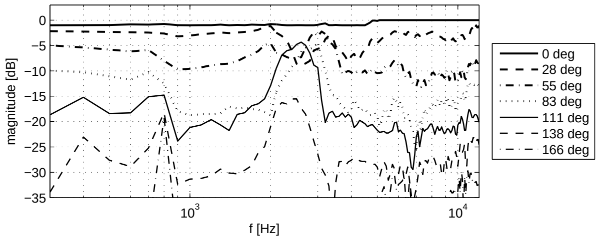

Fig. 11: *Normalized beamformer frequency responses (0 dB represents the desired on-axis frequency response) at seven control points on the measurement circle of radius $r = 2$ m enclosing the loudspeaker array.*

Apart from the mid-frequency anomalies of some of the rear directions, it could be said that the loudspeaker array achieves good wideband directivity. For its foreseen practical applications (described in the following section), the achieved performance is quite satisfactory.

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[7] The responses in the other two quadrants look very similar.

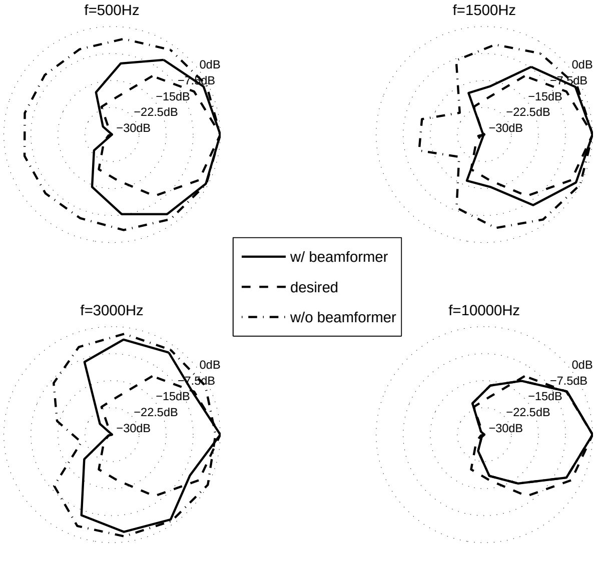


Fig. 12: *Beamformer directional responses at 13 control points on the measurement circle of radius $r = 2$ m enclosing the loudspeaker array.*

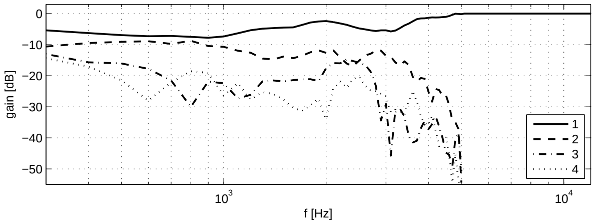


Fig. 13: *Beamformer filters' frequency responses shown for four loudspeakers of the array.*

Fig. 13 shows the frequency responses of the beamformer filters. As expected, the frequencies above $f_0 = 5$ kHz are reproduced only by the front loudspeaker. Below $f_0 = 5$ kHz, all loudspeakers are active, and the frequency responses exhibit smooth transitions between beamforming and using only the main loudspeaker. This smoothness enables implementing the beamformer with short FIR filters. Conversion of the filters' frequency responses to FIR filters is thoroughly described in [11].

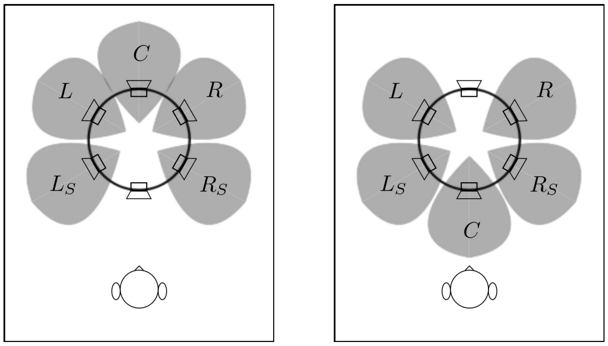
6. APPLICATIONS

As briefly mentioned in the introduction, one can foresee a number of uses for a loudspeaker system having high broadband directivity.

One possible application is mitigation of adverse effects of a listening room on the reproduced sound. Although the listening room contributes to the naturalness and gives an important sense of space, its low-frequency modes can severely impair the reproduced sound. Bad interaction of a loudspeaker system and listening room has a detrimental effect on intelligibility of the played content, be it speech or vocals. A directional loudspeaker reduces the strength of reflections and excites less room modes, and thereby reduces unwanted coloration and lengthy reverberation tail.

Another application where described loudspeaker array can be useful is targeted sound reproduction, as in PA systems, where it helps reducing "sound pollution".

Last, but not least, the loudspeaker array with high broadband directivity and steering capability can be used for reproducing surround (e.g., stereo or 5.1) contents in rooms. More specifically, using the capability to steer the reproduced sound, it is possible to "project" channels towards different walls in order to evoke auditory events outside the loudspeaker array, widen the auditory scene, and generate ambiance.



(a) (b)

Fig. 14: *Examples of 5.1 surround content reproduction with a six-element circular loudspeaker array. (a) Projecting front channels towards the front wall and surround channels towards side walls. (b) Similar to (a), but the center channel gets projected towards the listener in order to position the dialog or vocal at the loudspeaker array.*

Fig. 14 illustrates two examples how the loudspeaker array described in Section 5 can be used for reproducing 5.1 surround content. In the example shown in Fig. 14(a), the front channels get projected towards the front wall in order to widen the frontal auditory scene, while the two surround channels get projected towards the side walls to create ambience and extend the auditory scene towards the sides. Fig. 14(b) illustrates a slightly modified reproduction strategy, where the center channel gets projected towards the listener in order to anchor the dialogue or vocal to the loudspeaker array.

We have done informal listening tests on various 5.1 contents reproduced using our six-loudspeaker prototype. With both of the previously described strategies, we were able to generate convincing spatial effects from both the front and side walls of the listening room. Furthermore, the loudspeaker array did not suffer from timbral artifacts at any direction.

7. CONCLUSIONS

The goal of the work described in this paper was to design a compact loudspeaker array having wideband high directivity, with the ability to steer the sound to a number of different directions.

As a solution, we have proposed a beamformer for circular loudspeaker array which relies on two principles. One is the high-frequency directivity increase of a loudspeaker when mounted on a rigid cylindrical baffle. Since the baffle makes high-frequency directional response of a loudspeaker approximately frequency-invariant, a single loudspeaker is sufficient for reproducing high frequencies. The other principle is super-directional beamforming, which is an array technique that uses all loudspeakers at low frequencies in order to achieve the directional response of a single loudspeaker at high frequencies.

The effectiveness of the proposed approach was verified through simulations using a model of a baffled piston loudspeaker, and also with a prototype cylindrical loudspeaker array. Informal listening tests showed promising results in applications such as mitigating the adverse room effects, and surround sound playback in rooms.

8. ACKNOWLEDGMENTS

This work was supported by the National Competence Center in Research on Mobile Information and Communication Systems (NCCR-MICS, http://wwww.mics.org), a center supported by the Swiss National Science Foundation under grant number 5005-67322. The authors would like to thank Hervé Lissek from EPFL's Electromagnetics and Acoustics Laboratory (LEMA) for his help in making the anechoic measurements.

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