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A personal, 3D printable compact spherical loudspeaker array

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ABSTRACT

Compact spherical loudspeaker arrays exhibit controllable directivity, and electroacoustic musicians have recently become interested in using their beamforming capacities to compose spatial music. In particular, directivities of 3rd-order or higher turned out to offer a sufficiently precise horizontal control. Our engineering brief proposes the 170 compact spherical loudspeaker design that is DIY-3D-printable and only uses 8 audio channels. The 170 array houses seven 2.5” broadband transducers that allow third-order horizontal beamforming and a 6” subwoofer. We make the CAD model, electroacoustic measurements, and control filters openly accessible and show its beampatterns for verification, based on those measurements.

1 Introduction

Spherical beamforming for electroacoustic music applications was first described by Warusfel [1] with ircam’s La Timée loudspeaker arrays, and several authors such as Avizienis, Schmeder [2, 3], Pollow [4], and Pasqual [5] dealt with compact spherical loudspeaker beamformers thereafter.

At IEM, the icosahedral loudspeaker (IKO) has been developed since 2006 [6, 7, 8, 9, 10]. It is a strongly directional 3rd-order beamformer, specified quite powerfully, and capable of playing concerts for a couple of hundred people. To make its artistic use and remarkable effects available to a broader public, the IKO by IEM and sonible is manufactured by the company sonible GmbH `https://iko.sonible.com` and can be bought together with a suitable, powerful amplifier including interfacing. Despite several artists having already worked with it and played concerts, the IKO with individually 250W driven 20 channels is more of a performance device rather than a personal rehearsal instrument.

Therefore a first cheaper and do-it-yourself capable spherical beamforming variant has been considered in the work of Meyer-Kahlen [11] with the IEM loudspeaker cubes, however due to the much less pronounced 1st-order beamforming, it was recommended to use multiple of these cubes to get impressive surround-with-depth effects in the work of Deppisch [12].

As a second, and much more promising effort closer to the expressive performance of the IKO, Riedel [13] developed the mixed-order 393 loudspeaker that is a powerful 4th-order horizontal beamformer of much

(a) CAD model **(b)** Prototype **(c)** H3V1 **(d)** H3V0

Fig. 1: Model and prototype of the 170 loudspeaker array and the selected 3rd-order hoizontal spherical harmonics with and without the 1st-order vertical component.

smaller size. It can also work as a single performance device or rehearsal instrument, and moreover, it can be 3D printed, which facilitates a do-it-yourself reproduction. And yet, its three rings of 3, 9, and 3 loudspeakers still require to supply 15 individually amplified loudspeakers, and a separate subwoofer, rendering the required additional equipment a bit costly or at least not as compact as desirable for personal use.

When comparing the IKO, loudspeaker cubes, and 393 loudspeakers with the third author, the motivation was found to develop a device of still sufficiently high horizontal beamforming capacity but driven with typical 8-channel equipment (interface, amplifier) to vastly reduce hardware costs. In this e-brief, we present the resulting prototype called 170, its openly accessible design, measurement data, and control filters.

2 Design and Construction

The loudspeaker layout was chosen to enable 3rd-order horizontal and 1st-order vertical Ambisonics beamforming. To meet these specifications a broadband sub-loudspeaker (SB Acoustics SB17CRC35-4 6") was placed on the top of the sphere and a ring of seven broadband transducers (Fountek FR88EX 3") were positioned on a horizontal ring at $-10°$ elevation.

Due to the benefits in high availability and costs of 3D-printing technology as well as the propitious acoustic results of the 393 we designed a CAD-model for the housing. Our prototype was created by an ordinary printer of $250x210x200$ mm build volume using PLA as a material with 25% infill.

3 Filter Design

As described in [13] a mixed-order filter design approach provides highly sophisticated controllability in resolution for an Ambisonics beamformer.

3.1 MIMO Acoustic-Decoupling-Filters (ADF)

Using a Laser-Vibrometer, acoustic coupling between the loudspeakers was measured and a MIMO crosstalk canceller was applied to equalize each driving path. The system $\boldsymbol{T}$ can be described as multiple-input-multiple-ouput system

$$\boldsymbol{v} = \boldsymbol{T}\boldsymbol{u} \tag{1}$$

in the frequency domain, whose inversion would yield frequency-dependent voltages as acoustic decoupling filters (ADF) that control the velocities independently. The corresponding measurements are openly accessible[1]. As described in [13], instead of system inversion as is, it is better to invert only after separating the active paths in $\boldsymbol{T}$ from their minimum-phase response $\boldsymbol{T}_{\mathrm{eq}} = \mathrm{diag}\{\mathrm{diag}\{\boldsymbol{T}\}^{-1}_{\mathrm{minph}}\}$ from the voltage side to $\boldsymbol{T} \leftarrow \boldsymbol{T}\boldsymbol{T}_{\mathrm{eq}}$, only keeping cross-talk paths inside the zero-phase band pass H_{BP} that contains the critical frequency range 80Hz-1.4kHz for beamforming

$$\boldsymbol{T} \leftarrow \mathrm{diag}\{\mathrm{diag}\{\boldsymbol{T}\}\} + H_{\mathrm{BP}}[\boldsymbol{T} - \mathrm{diag}\{\mathrm{diag}\{\boldsymbol{T}\}\}]. \tag{2}$$

For H_{BP} the absolute-square of a 4th-order Butterworth bandpass was used. The resulting MIMO ADF $\boldsymbol{T}^{-1}$ from this matrix is combined with an equalizer $\boldsymbol{T}_{\mathrm{eq}}$ of every active path to the average

[1]https://phaidra.kug.ac.at/detail/o:95559

original response of the mid-high-frequency transducers $T_{\mathrm{avg}} = \sqrt{\frac{1}{7}\sum_{i=2}^{8}|t_{ii}|^2}_{\mathrm{minph}}$, yielding the ADF $T_{\mathrm{avg}}\boldsymbol{T}_{\mathrm{eq}}\boldsymbol{T}^{-1}$. Moreover, to avoid inverting complicated transducer responses above 4 kHz, the ADF was faded into a scaled identity by an 8th-order Linkwitz-Riley crossover at 4 kHz. This ADF yields the shortest-possible filters, by mutually matching the channel responses instead of equalizing them to unity.

3.2 Spherical-Harmonic (SH) Beamforming

The driving velocities $\boldsymbol{v}$ for beamforming to an adjustable direction $\boldsymbol{\theta}$ are calculated using a mixed-order spherical harmonics (SH) beamforming system that synthesizes the SHs shown in either Fig. 1c or 1d, according to [13]. The synthesized SHs focus on the predominantly horizontal beampatterns, and in case of horizontal 3rd-order vertical 1st-order (H3V1) [14], include the dipole in z-direction that offers to synthesize beams to above or below. However, a purely horizontal H3V0 synthesis that uses the 6" transducer exclusively in the zeroth-order subwoofer band was found to sound deliver better robustness with regard to harmonic distortions and a more flexible low-frequency control, see Fig. 1d.

Decoder: A frequency-independent decoder is desinged to control SH velocities from the pseudo-inverse $(\boldsymbol{MA})^{\dagger}\boldsymbol{M}^{\mathrm{T}}$. A column in $\boldsymbol{A}$ describes SH coefficients of the l^{th} loudspeaker cone as spherical cap of the aperture α_l, and a binary mask $\boldsymbol{M}$ that selects the 7 H3V0 or the 8 H3V1 SHs from the 16 3rd-order SHs. The cap encoders $\boldsymbol{A}$ involve a vector of SHs $\boldsymbol{y}(\boldsymbol{\theta}) = [Y_n^m(\boldsymbol{\theta})]_{nm}$ sampled at a loudspeaker direction $\boldsymbol{\theta}_l$, and the Legendre polynomials $P_n(\cos\vartheta)$, [15],

$$\boldsymbol{D} = (\boldsymbol{MA})^{\dagger}\boldsymbol{M}^{\mathrm{T}}, \tag{3}$$

$$\boldsymbol{A} = [\mathrm{diag}\{\boldsymbol{a}^{(l)}\}\,\boldsymbol{y}(\boldsymbol{\theta}_l)]_l, \qquad \boldsymbol{a}^{(l)} = [a_{nm}^{(l)}]_{n,m} \tag{4}$$

$$a_{nm}^{(l)} = \begin{cases} 1-\cos\frac{\alpha_l}{2}, & n=0 \\ \frac{-\cos\frac{\alpha_l}{2}\,P_n(\cos\frac{\alpha_l}{2})+P_{n-1}(\cos\frac{\alpha_l}{2})}{n+1}, & n>0. \end{cases} \tag{5}$$

Radial Filters: To feed the decoder, the radial filters $\rho\,c\,\mathrm{i}^n\,k\,e^{\mathrm{i}kR}\,h_n'^{(2)}(kR)$ are required for directivity synthesis in terms of far-field SH sound pressure; the array radius is $R = 0.12$ m, the wave number $k = \frac{\omega}{c}$, $\omega = 2\pi f$, and $c = 343$ m/s. However, the filters need to be truncated depending on frequency. We used band passes H_b from [13] with crossovers $f_c = [130, 280, 350, 400]$ Hz for SH beamforming up to the 0th, 1st, 2nd, or 3rd order.

In every band, $b = 0,\ldots,3$, degree-dependent mixed-order corrected max-rE weights were used, with $M_n^m = 1$ for the selected H3V0 or H3V1 SHs, or $M_n^m = 0$ else,

$$w_{nm}^{(b)} = w_n^{(b)} \frac{\sum_{n=|m|}^{b}\frac{(2n+1)(n-|m|)!}{(n+|m|)!}w_n^{(b)}P_n^{|m|}(0)}{\sum_{n=|m|}^{b}M_n^m\frac{(2n+1)(n-|m|)!}{(n+|m|)!}w_n^{(b)}P_n^{|m|}(0)},$$
$$w_n^{(b)} = \frac{P_n(\cos\frac{\frac{\pi}{180^\circ}137.9^\circ}{b+1.51})}{\sum_{n=0}^{b}(2n+1)P_n(\cos\frac{\frac{\pi}{180^\circ}137.9^\circ}{b+1.51})}. \tag{6}$$

Altogether, this yields the radial filters

$$\rho_n(\omega) = \sum_{b=n}^{N}\rho\,c\,\mathrm{i}^n\,k\,e^{\mathrm{i}kR}\,w_{nm}^{(b)}\,H_b(\omega)\,h_n'^{(2)}(kR). \tag{7}$$

The H3V0 configuration turned out to be superior. There, the decoder was chosen to only produce a velocity for the 6" loudspeaker through the ADF in the zeroth-order band below 280 Hz, while actively impeding the others. By contrast, the higher bands synthesizing up to the 1st, 2nd, and 3rd order SHs only use velocities of the 7 horizontal 3" transducers through the ADF.

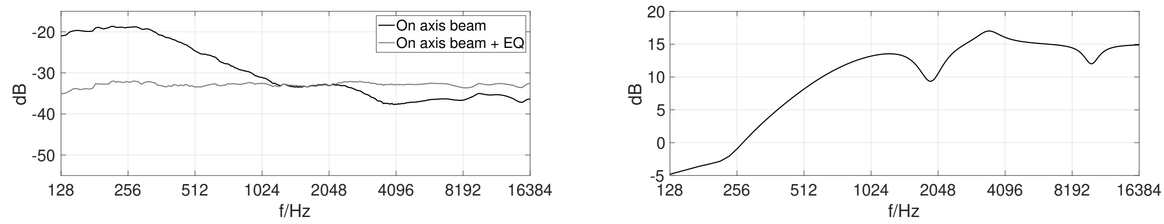
3.3 On-axis equalisation

The above ADF, decoding, and radial filtering avoided any common frequency responses a master EQ could equalize. Therefore an equalizer for the on-axis beam response was designed by acoustic measurement. Figure 2a shows the measured on-axis frequency response with and without equalization, and Figure 2b shows the equalization filter.

4 Beampatterns

In order to evaluate the resulting frequency depending beam width high resolution measurements in 10° azimuth and 10° elevation have been made. In Figure 3 the resulting directivity patterns are shown for a horizontal and a vertical profile of a beam at 0° azimuth. The high resolution measurements can be found here[2]. The vertical dispersion is as expected ±30° in a frequency range of 400Hz −1.6kHz.

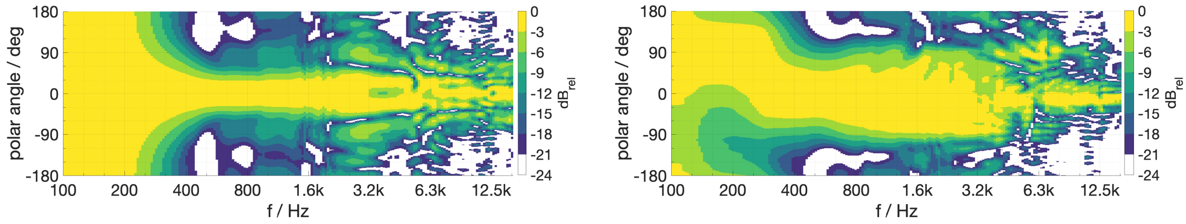
[2]https://phaidra.kug.ac.at/detail/o:95558



(a) On-axis response with/without EQ.

(b) Magnitude of the equalization filter.

Fig. 2: Frequency response equalization of the 170 array in the H3V0 configuration with ADF avoiding common responses, decoder, and radial filters.



(a) Horizontal Directivity

(b) Vertical Directivity

Fig. 3: Horizontal and vertical cross-section through the directivity pattern of the 170 loudspeaker array for horizontal beamforming to the azimuth 0°.

5 Playing the 170

Using the `mcfx-Convolver`[3] audio plugin the driving filters can be applied with ease in a multichannel DAW like `Reaper`. We provide `mcfx`-presets for controlling the horizontal beam, the zeroth-order monopole and overall on-axis equalization.

6 Conclusion

We presented the 170 loudspeaker, an spherical loudspeaker array design that is 3D printable and provides high horizontal resolution. It is meant to be useful for (but not limited to) making electroacoustic music and sound installations with it, and should inspire DIY reproduction as well as further research. A particular design aspect was to keep the costs low, and including eight-channel audio-interface and amplification, the typical costs would stay below €1500. The CAD model, transducer and component list, notes on 3D printing and its assembly, filter sets to make it work, and verification measurements are made openly available on the website `https://iaem.at/projekte/sphericalarrays/170-loudspeaker`.

[3]http://www.matthiaskronlachner.com/?p=1910

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