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The Effect of Loudspeaker Radiation Properties on Acoustic Crosstalk Cancelation Using a Linear Loudspeaker Array

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Abstract

Acoustic crosstalk cancelation refers to the process of driving a set of loudspeakers such that the produced total sound field illuminates one ear of a listener and cancels out on the other ear. This allows for imposing binaural localization cues on the signals by means of head-related transfer functions and thereby make the listeners localize sound sources from directions where there are no loudspeakers. In [1-3], we proposed a system that uses a linear array of loudspeakers and superdirective beamforming to perform listener-position-adaptive crosstalk cancelation. The original beamformer employed a point-source model for the loudspeakers. We show in this contribution that the actual loudspeaker radiation departs significantly from that of the point source model. We demonstrate that the measured channel separation between left and right ear increases significantly in the frequency range of 1-2 kHz as well as below 700 Hz when the actual loudspeaker radiation properties are accounted for in the beamformer design.

Introduction

Crosstalk cancelation (CTC) has been pursued since the 1960s [4]. Most of the early implementations employed a pair of loudspeakers with a loudspeaker positioned ipsilateral to each of the ears of the listener, respectively. The crosstalk of each loudspeaker to the corresponding contralateral ear was estimated by different means, and a cancelation signal was emitted by the other loudspeaker. Numerous authors have contributed to the field. We refer the reader to the references in, for example, [1-3] for a non-exhaustive list.

Starting in the 1990s, researchers have been evaluating the capabilities of loudspeaker arrays to perform acoustic CTC [5] with just as many contributors as to two-channel CTC. We again refer to the references in, for example, [1-3].

System Design

The system that we presented in [1-3] employs a linear equi-spaced 8-channel loudspeaker array as depicted in Fig. 1. The geometry of the scenario under consideration is depicted in Fig. 2. The core of the system is a convex superdirective nearfield beamformer that directs a beam to one of the ears of the listener and produces a null at the other (contralateral) ear. Assuming that the loudspeakers emit ideal spherical waves, then the transfer functions from one of (the two)

Fig. 1: Example prototype using 8 Neumann KH 80 DSP loudspeakers with a spacing of 154 mm

input channels of the system to the ears of the listener that is assumed to be located centrally at 1 m distance to the array show a channel separation of at least 20 dB over the vast part of the audible frequency range as depicted in Fig. 3.

Fig. 3 also reveals that the channel separation drops significantly below 1 kHz as soon as some amount of mismatch of the sensitivity of the loudspeakers and uncertainties in the loudspeaker placement are included in the simulation.

This reduction of the channel separation at low frequencies is not surprising as we are looking at a frequency range in which the two control points, the ears, are separated by less than a wavelength.

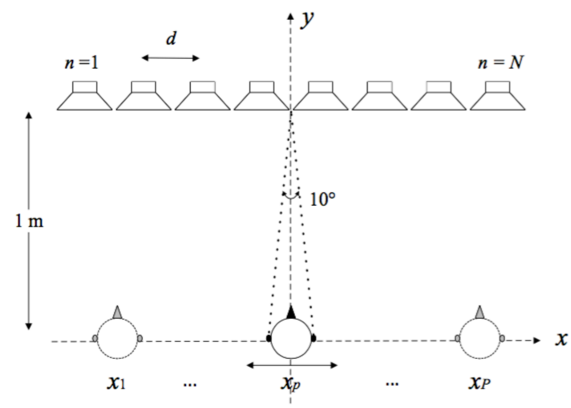

Fig. 2: System geometry; the enabled listening locations are along a line parallel to the array

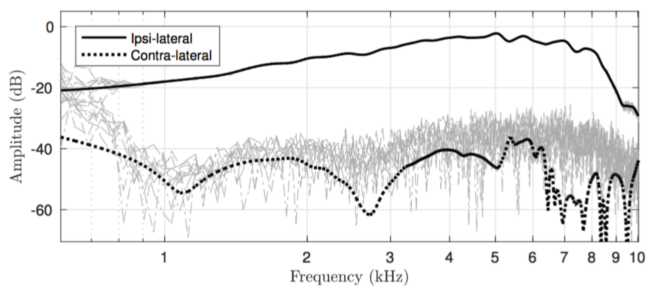

Fig. 3: System transfer function to the two ears of the listener under ideal conditions (black lines) as well as with simulated loudspeaker mismatch (gray lines) (data from [1])

We therefore chose to use the beamformer only above 1 kHz and recursive ambiophonic crosstalk elimination (RACE) [6], which is a simple two-channel CTC method that has shown to be effective and degrade gracefully.

Translations of the listener are enabled by pre-computing the beamformer weights for a set of listener positions and subsequent parameterization as presented in [2,3].

Measurements on a prototype employing Genelec 8020 loudspeakers under anechoic conditions for different listening positions are depicted in Fig. 4. They show that the channel separation is significantly lower than predicted.

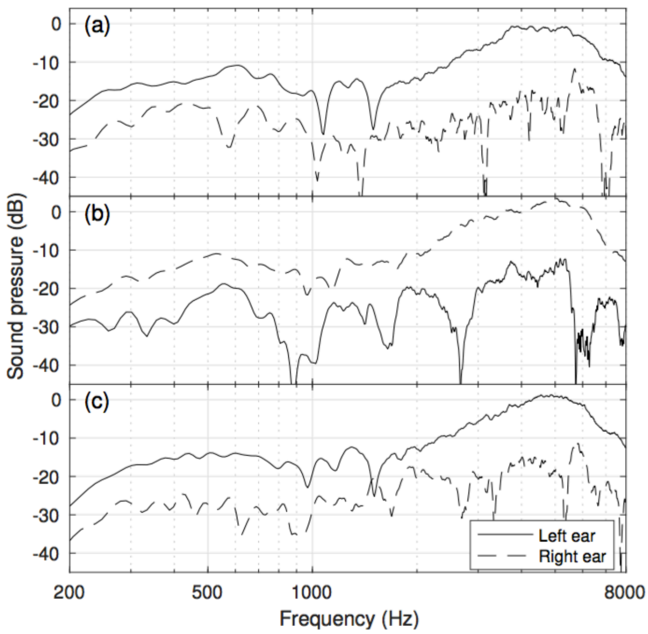

Fig. 4: Measured transfer functions at the ears of a KEMAR manikin. (a, b) depict results when KEMAR is positioned at a distance of 1 m to the array and 30 cm left to the array center. (a) left ear is the illuminated ear; (b) right ear is the illuminated ear. (c) depicts the transfer function when KEMAR is at the array center, and the left ear is the illuminated one. The data are from [3].

Incorporation of Measured Loudspeaker Directivities

We built a new prototype composed of Neumann KH 80 DSP loudspeakers (Fig. 1), which turned out to be more practical as they exhibit various reproducible gain settings that are digitally matched by the manufacturer to avoid mismatch.

We measured the directivity of each of the loudspeakers inside the array under anechoic conditions along an arc of 1.00 m radius with its center at the center of the array and with a spacing of 1°. The directivities of loudspeakers 1 and 4 are depicted in Fig. 5. It can be seen that they clearly depart from a spherical wave.

We then computed the beamformer weights based on the measured directivities instead of on the spherical wave model (as we did it in Fig. 3). Fig. 6 depicts the resulting channel separation.

Fig. 6 reveals that the incorporation of the measured directivities increases the channel separation by up to 15 dB in the frequency range between 1 and 2 kHz as well as below 700 Hz but does otherwise have no influence. The frequency range in which this improvement occurs is where the channel separation is lowest and which is important of lateralization when binaural signals are presented. A broadband channel separation of the 20 dB or more is apparent, and we can confirm through informal listening that the incorporation of the measured directivities has a clearly audible effect. We will further investigate the possible improvements that may be achievable at lower frequencies as well as the effect of reflecting surfaces on the presentation of binaural signal via our prototype in [7].

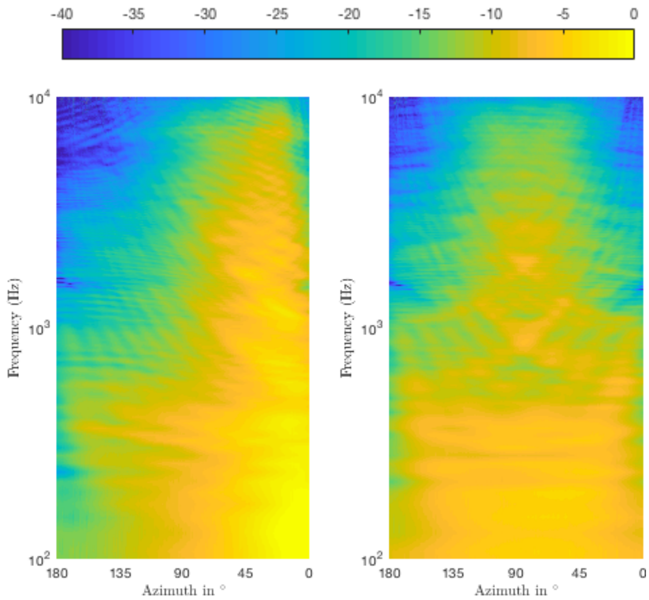

Fig. 5: Measured directivities in dB of loudspeakers 1 (left) and 4 (right); the abscissa specifies the azimuth of the measurement locations along a semicircle around the center of the loudspeaker array

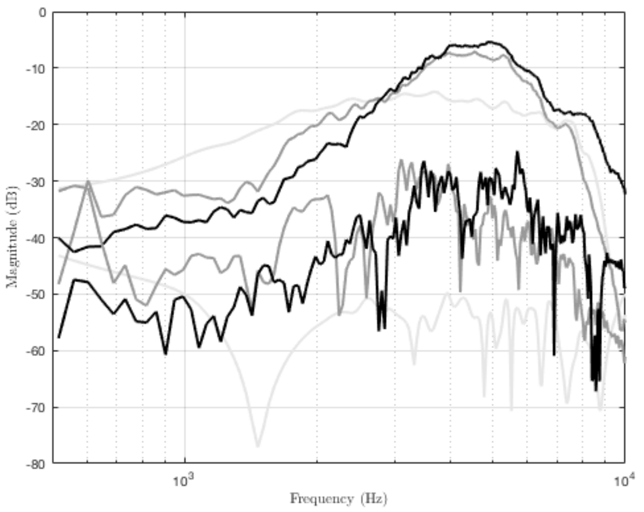

Fig. 6: Channel separation at illuminated and contralateral ear under ideal conditions and assuming a spherical head (light gray), at the ears of a KEMAR manikin with the beamformer computed based on the spherical wave assumption (dark gray), as well as at the ears of a KEMAR manikin with the beamformer computed based on the measured directivities (black).

Conclusions

We investigated the effect of incorporating measured loudspeaker directivities in the beamformer design of an array-based crosstalk-cancelation system. The improvement compared to assuming spherical wave radiation is limited but clearly audible.

Acknowledgements

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