Auralization of Nearby Sound Sources - Part 1: Near-Field Model

Christian Borß

Institute of Communication Acoustics, Ruhr-Universität Bochum, 44780 Bochum, Germany, Email: christian.borss@rub.de

Abstract

The auralization of nearby sound sources can generally be improved, if near-field effects are simulated. This can be achieved with a Head-Related Transfer Function (HRTF) database which contains transfer functions for various distances. However, measuring HRTFs for various distances is a tedious task.

In our approach we strive to model the related effects with less complexity. We distinguish between source- and head-related near-field effects and model them by time-variant filters. By doing so, we account for the additional low frequency boost in the near-field of directional sound sources. We further present a method for critically sampling the distances for which the distance variation filters are determined. A measurement with two dummy heads used as speaker/listener confirms that the low frequency boost can be predicted quite well with the proposed model [1].

Near-Field Model

To point out some properties related to the near-field of directional sound sources i.e., the low frequency boost, we first consider the sound pressure field $P_l^m(r,\theta,\phi,\omega)$ of an acoustical multipole of degree l and order m given in spherical coordinates $[r,\theta,\phi]^T$. According to the Stokes-Rayleigh solution of the Helmholtz equation [2, Sec. 19.4.1], $P_l^m(r,\theta,\phi,\omega)$ can be written in the following form:

$$P_l^m(r,\theta,\phi,\omega) = S_l(r,\omega)\widetilde{P}_l^m(\theta,\phi,\omega)G(r,\omega) \quad , \qquad (1)$$

where $G(r,\omega)$ denotes the free-space Green's function and $\widetilde{P}_l^m(\theta,\phi,\omega)$ denotes the far-field directivity which is a weighted version of the spherical harmonic $Y_l^m(\theta,\phi)$. The details of the near-field are taken into account by the Stokes function which we denote as $S_l(r,\omega)$ and which is defined by the following series [2, p. 386]:

$$S_l(r,\omega) = \sum_{k=0}^{l} \frac{(l+k)!}{2^k k!(l-k)!}\left(\frac{c}{j\omega r}\right)^k \quad . \qquad (2)$$

This polynomial specifies the low-frequency boost which can be observed in the proximity of the sound source.

Deviding (1) by the free-space Green's function $G(r,\omega)$ and considering arbitrary point sources yields what we denote as Source-Related Transfer Function (SRTF) $H_\mathrm{s}(r,\theta,\phi,\omega)$. This definition is reciprocal to the well known definition of the Head-Related Transfer Function (HRTF) [3, 4]. Consequently, an HRTF $H(r,\theta,\phi,\omega)$ can be split in a far-field component $\widetilde{H}(\theta,\phi,\omega)$ and a near-field component $D(r,\theta,\phi,\omega)$ which we denote according to [5] as distance variation function (DVF),

$$H(r,\theta,\phi,\omega) = D(r,\theta,\phi,\omega)\widetilde{H}(\theta,\phi,\omega) \quad . \qquad (3)$$

The DVF accounts for the changed diffraction around the head which results in a coarse frequency emphasis by shadowing and proximity effects. While the far-field component contains the main directional and by this the main individual features of the transfer function, we can assume that the near-field component contains less individual features. Hence, the simulation of near-field effects can be simplified by making a far-field measurement only and by applying DVFs which have been determined from e.g., dummy head HRTFs or from an analytical model. As stated in the previous paragraph, mainly the low frequencies are affected by the near-field effects. For low frequencies, the diffraction around a human head can be approximated in first order by the diffraction around a sphere. Hence, if we want to simulate a human speaker in the proximity of a human receiver, we can use DVFs derived from sphere HRTFs [6] to model source-related *and* head-related near-field effects. Such a near-field model was proposed by Kan, Jin, and van Schaik for HRTFs [5]. The model presented in this paper is a unified model for source-related and head-related near-field effects.

The near-field HRTFs specified in (3) are valid for an omnidirectional sound source while the near-field SRTFs are valid for an omnidirectional receiver. A proximate solution for a unified near-field model can be found by a notational substitution of the directional sound source by an omnidirectional reference source whose sound pressure field is given by the product of the free-space Green's function and the SRTF evaluated at the receiver position. This allows for approximating the sound pressure at the ear canal entrances as follows for a given source orientation $[\theta_\mathrm{s},\phi_\mathrm{s}]^T$ and receiver orientation $[\theta_\mathrm{r},\phi_\mathrm{r}]^T$:

$$P_\mathrm{l}(r,\theta_\mathrm{s},\phi_\mathrm{s},\theta_\mathrm{r},\phi_\mathrm{r},\omega) \approx H_\mathrm{s}(r,\theta_\mathrm{s},\phi_\mathrm{s},\omega)G(r,\omega)\ldots D_\mathrm{l}(r,\theta_\mathrm{r},\phi_\mathrm{r},\omega)\widetilde{H}_\mathrm{l}(\theta_\mathrm{r},\phi_\mathrm{r},\omega) \qquad (4)$$

$$P_\mathrm{r}(r,\theta_\mathrm{s},\phi_\mathrm{s},\theta_\mathrm{r},\phi_\mathrm{r},\omega) \approx H_\mathrm{s}(r,\theta_\mathrm{s},\phi_\mathrm{s},\omega)G(r,\omega)\ldots D_\mathrm{r}(r,\theta_\mathrm{r},\phi_\mathrm{r},\omega)\widetilde{H}_\mathrm{r}(\theta_\mathrm{r},\phi_\mathrm{r},\omega) \; . \qquad (5)$$

Critical Sampling

Plotting sphere DVFs for various distances reveals a noticeable similarity of the considered functions and suggests a reciprocal relation of the distance and the amplitude response in dB. Under the assumption that this approximation holds for all directions and frequencies, the DVF can be roughly approximated as follows:

$$|D(r,\theta',\omega)| \approx |D(r_0,\theta',\omega)|^{\frac{1}{c_0+c_1 r}} \quad , \qquad (6)$$

where θ' denotes the elevation angle of the axially symmetrical sphere DVF and r_0 denotes the reference distance which is used as a constraint.

If an auralization software simulates near-field effects by using time-variant FIR filters, then it is desirable to have DVF filter coefficients which are similar enough that a simple commutation of the filter coefficients results in no audible artifacts. Hence, the tabulated distances ρ_n should be chosen such that switching from $D(\rho_n, \theta'_m, \omega)$ to $D(\rho_{n+1}, \theta'_m, \omega)$ and vice versa results in no audible artifacts for any tabulated angle θ'_m. On the other hand, it is desirable to store the DVFs only for a minimum number of distances i.e., to use critical sampling. This requirement is met, if the maximum gain difference between two DVFs is just below the detection threshold Δg for artifacts caused by the commutation,

$$\max_m \left(20 \log_{10} \left| \frac{D(\rho_{n+1}, \theta'_m, \omega)}{D(\rho_n, \theta'_m, \omega)} \right| \right) = \Delta g \quad . \tag{7}$$

This means that the maximum gain factors for the distances ρ_n must be an integer multiple of Δg. Evaluating (6) for $\theta' = 0°$ and $\omega = 2\pi 20$ Hz (global maximum of the DVF) and inserting it into (7) multiplied with n results in $n\Delta g \approx g_0/(c_0 + c_1\rho_n)$ where g_0 is the gain factor for the reference distance r_0 in dB. This yields the critically sampled distances,

$$\rho_n = \frac{1}{c_1} \left(\frac{g_0}{n\Delta g} - c_0 \right) \quad . \tag{8}$$

Measurement

In order to evaluate the proposed near-field model, we investigated the transfer characteristic of a human speaker in the proximity of a human receiver. Using a "talking" dummy head (HEAD acoustics "HMS II.3") as a directional sound source, we measured the transfer functions to the ear canal entrances of a second dummy head (HEAD acoustics "KMS 3") using a blocked ear canal measurement method [4]. With regard to the intended listening test, only a limited set of distances (40 cm, 80 cm, and 160 cm) and directions (-110°, -30°, 0°, 30°, and 110°) were measured using a 13th order Maximum Length Sequence (MLS). Figure 1 shows some of the measured near-field HRTFs (solid) i.e., for the left ear and a sound source located at $-110°$ (left) in 40 cm (red), 80 cm (blue), and 1.60 m (black) distance. The dashed graphs shown in this figure are the transfer functions predicted from the product of the far-field HRTF (measured in 1.60 m distance), a spherical DVF, and a spherical SRTF. As can be observed, our near-field model results in a proper prediction of the low frequency boost.

Conclusions

The unified near-field model presented in this paper can be used to improve the auralization of nearby sound sources. The split-up of the involved transfer functions into a product of lower dimensional functions allows for a filter realization using critical distance sampling. The

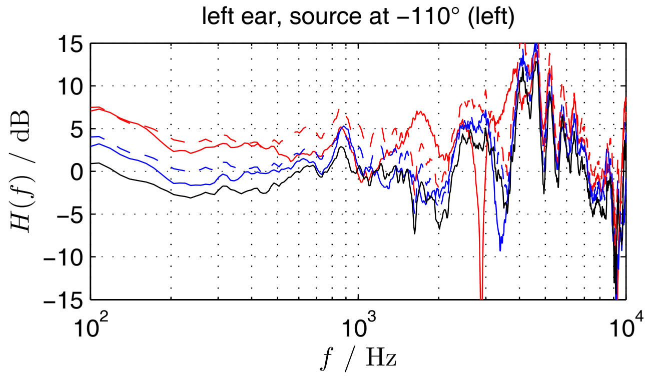

Figure 1: Near-field HRTFs for 40 cm (red), 80 cm (blue), and 1.60 m (black) source distances (solid: measured HRTFs including equalization for the measuring loudspeaker and for a Beyerdynamic DT-770 headphone; dashed: HRTFs predicted from the product of a far-field HRTF, a spherical DVF, and a spherical SRTF)

presented measurement confirms that the low frequency boost can be predicted quite well with the proposed model. The deviation at higher frequencies is subject of the listening test described in the second part ("Auralization of Nearby Sound Sources - Part 2: Evaluation").

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