Perceptual Relevance of Acoustic Radiation Patterns

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Abstract

The radiation pattern of an acoustic source describes how the sound wave propagates from the source in a free space. In the general case, the radiation pattern is represented as a function on the surface of a unit sphere which is dependent both on direction and frequency. The combination of radiation patterns in binaural room acoustics models can improve the performance of virtual acoustics systems in the context of reproducing the acoustic field generated by realistic sources with relation to human hearing. The perceptual relevance of acoustic radiation patterns in virtual acoustic environments is evaluated in this work on a physical signal-related basis using monaural room impulse responses (RIRs). The physical evaluation of this perceptual relevance includes the calculation of room acoustical parameters, which are used as predictors of the potentially perceived sound field when binaural RIRs are employed.

Introduction

Room simulation models may be used in order to perform auralization in virtual acoustics systems. Well known room simulation methods that can be used with wideband signals include the ray tracing method [1], the image method [2], later modified to smooth the reflections in the time domain [3], and a hybrid combination of these two approaches, such as the *real-time framework for the auralization of interactive virtual environments* (RAVEN) [4]. These models usually describe a point-to-point *room impulse response* (RIR). In order to auralize the sound signals in the room, the *head related transfer functions* (HRTFs) [5,6], can be used to simulate the directivity of the receiver [4] in the process of the RIR generation.

However, the combination of acoustic source radiation patterns in room acoustics models may also improve the performance of virtual acoustics systems, and yet the study of the acoustic source radiation pattern effect on the performance of auralization systems is limited in the literature. The radiation pattern of an acoustic source describes how the sound wave propagates from the source in a free space and may be represented using a function on the surface of a unit sphere [7, 8]. Many attempts were performed in order to experimentally characterize the radiation pattern of musical instruments. Examples include the measuring of the radiation pattern of different musical instruments in averaged octave bands [9], icosahedral array of 12 microphones with stringed musical instruments [10], a linear array of 15 microphones with a mechanically excited violin [11], and two circular arrays using a total number of 13 microphones with three wind instruments [12]. More extensive analysis of the radiation pattern include a spherical array of 64 microphones with a violoncello, three brass, and five woodwind instruments [13], a spherical array of 22 microphones with 14 common orchestral instruments and a singer [14], and a spherical array of 32 microphones with 42 historical and modern musical instruments with human players, recorded in the *Technical University of Berlin* (TU Berlin) [15–17].

This work investigates the effect of the acoustic source radiation pattern that is employed in room acoustics models on the perceptual room parameters, as a first step towards the understanding on its effect on auralization. The radiation pattern database of musical instruments that was recently recorded in TU Berlin [15–17] was used. The image method room acoustic model [2] was extended, so that it includes the radiation pattern of the acoustic source and a figure-of-eights microphone directivity, which is required for some perceptual parameters. The perceptual parameters are calculated from the ISO 3382-1:2009 standard [18].

Acoustic source radiation pattern

The radiation pattern may be given along a surface of a sphere in the spherical harmonics domain using

$$p\left(k,\theta,\phi\right)=\sum_{n=0}^{\infty}\sum_{m=-n}^{n}p_{nm}\left(k\right)Y_{n}^{m}\left(\theta,\phi\right)\quad , \qquad (1)$$

where $p\left(k,\theta,\phi\right)$ is the pressure at a wave number k, an elevation θ, and an azimuth ϕ, and $Y_n^m\left(\cdot,\cdot\right)$ is referred to as the spherical harmonic of order n and degree m.

The coefficients $p_{nm}\left(k\right)$ define the radiation pattern at a wave number k. These coefficients can be estimated from a surrounding spherical microphone array measurements using a minimal error criterion between the measurements and the reconstructed values at the measurements angles using Eq. (1).

Thus, the acoustic radiation pattern is frequency dependent and, therefore, should be defined for each frequency band. In case the acoustic source is a musical instrument, each played note has a radiation pattern for each one of its associated overtones. For this reason, the radiation pattern in each frequency band is measured by averaging the radiation patterns of all overtones, of which their frequencies are in this band. This procedure includes all overtones from all the notes that are playable on that instrument.

Implementation of an acoustic source radiation pattern in the image method

The image method of Allen and Berkley defines a point-to-point RIR. In order to employ a radiation pattern on the source, such that of Eq. (1), the image method should be modified, so that radiation patterns are mirrored instead of monopole source points. This is performed by reversing the angles in Eq. (1), and multiplying the ith reflection gain h_i with an arrival direction of (θ_i, ϕ_i) by $\left|p\left(k, \xi_i^\theta\left\{\theta_i\right\}, \xi_i^\phi\left\{\phi_i\right\}\right)\right|$, where ξ_i^θ and ξ_i^ϕ are the mirroring operators of the ith reflection, applied on the elevation and azimuth, respectively.

ISO 3382:2009 perceptual parameters

Table 1 shows the acoustic quantities, which are related to the listener hearing aspects in a room. These parameters include the sound strength (G), early decay time (EDT), clarity (C_{80}), definition (D_{50}), centre time (T_S), early lateral energy fraction (J_{LF}), and late lateral sound level (L_J). These parameters are defined and formulated in ISO 3382-1:2009 [18].

Table 1: Acoustic quantities grouped according to listener aspects, after ISO 3382-1:2009 [18]

Subjective listener aspect	**Acoustic quantity**	**Just noticable diference (JND)**
Subjective level of sound	Sound strength, G	1 dB
Perceived reverberance	Early decay time, EDT	5 %
Perceived clarity of sound	Clarity, C_{80}	1 dB
	Definition, D_{50}	0.05
	Centre time, T_S	10 ms
Apparent source width (ASW)	Early lateral energy fraction, J_{LF}	0.05
Listener envelopment (LEV)	Late lateral sound level, L_J	Not known

Experimental Results

The radiation pattern of a guitar was measured using a surrounding spherical array of 32 microphones in an anechoic chamber at TU Berlin [15] and rearranged into third-octave bands. The image method of Allen and Berkley [2] was modified in such a manner, that the reflections are multiplied by the corresponding mirrored radiation pattern at the reflection angle. The room dimensions were $10 \times 10 \times 5$ m^3. The acoustic source was located at $(2, 5, 0.5)$ m, corresponding to a stage position, and 64 microphones were placed in a cubical area of dimensions $2 \times 2 \times 0.5$ m^3 around $(6, 5, 1.5)$ m, corresponding to an audience region.

Figures 1-7 show the results of the perceptual room acoustical parameters from Tab. 1 for the cases of a monopole source and a source with a radiation pattern of a guitar. The graphs indicate the mean values along the different spatial locations in the room throughout all 64 microphones. The vertical bars indicate the standard deviation.

While the difference between the response of a monopole and the directional source seems to be small for most of the parameters, it may be seen that there is a significant difference in J_{LF} at frequencies higher than 1 KHz. This result implies on a wider listener envelopment perceived by the listener when a realistic source with a directional radiation pattern is used.

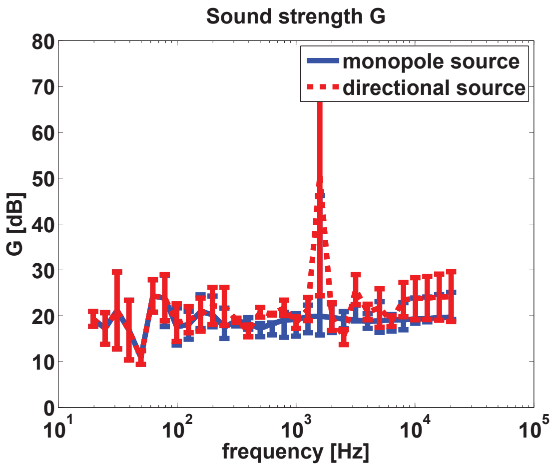

Figure 1: Sound strength results using a monopole and a radiation pattern of a guitar.

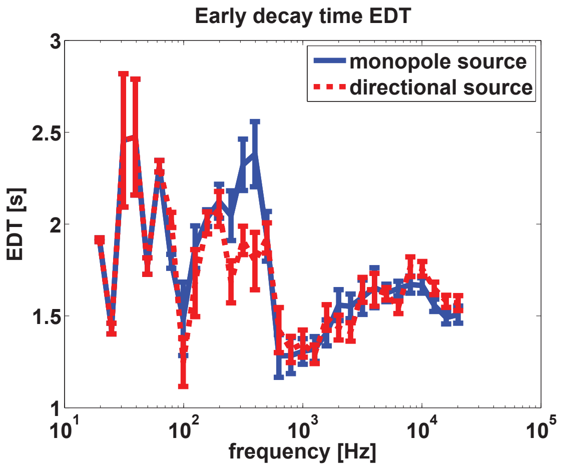

Figure 2: Early decay time results using a monopole and a radiation pattern of a guitar.

Conclusion

The effect of the radiation pattern of an acoustic source on perceptual room acoustical parameters were investigated. It was found that a wider listener envelopment may be perceived by the listener when an acoustic source with a directional radiation pattern is used, rather than

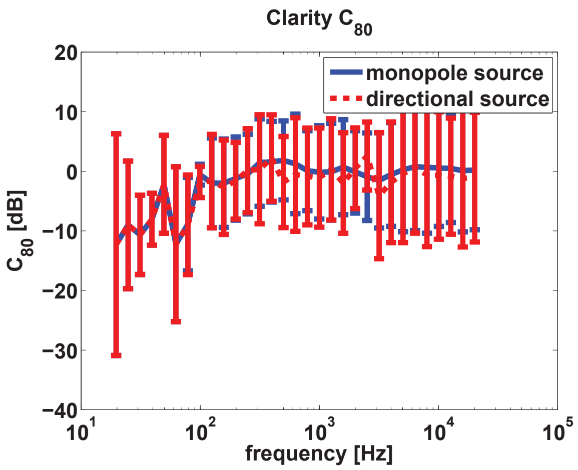

Figure 3: Clarity results using a monopole and a radiation pattern of a guitar.

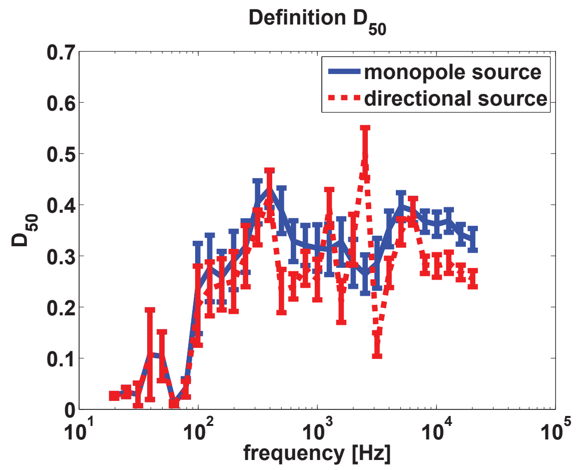

Figure 4: Definition results using a monopole and a radiation pattern of a guitar.

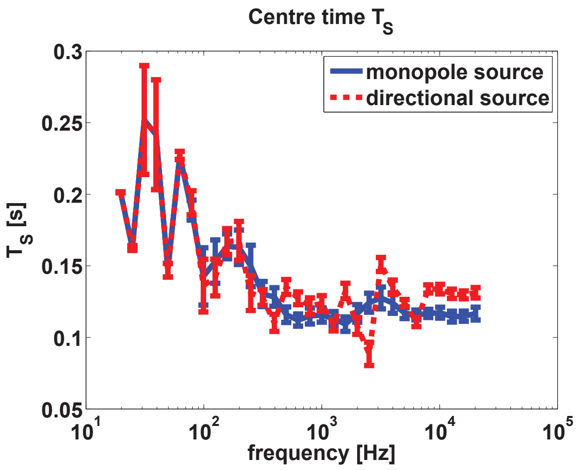

Figure 5: Centre time results using a monopole and a radiation pattern of a guitar.

a monopole source. This study has been performed using the image method and a future work may include scattering models and a listening test.

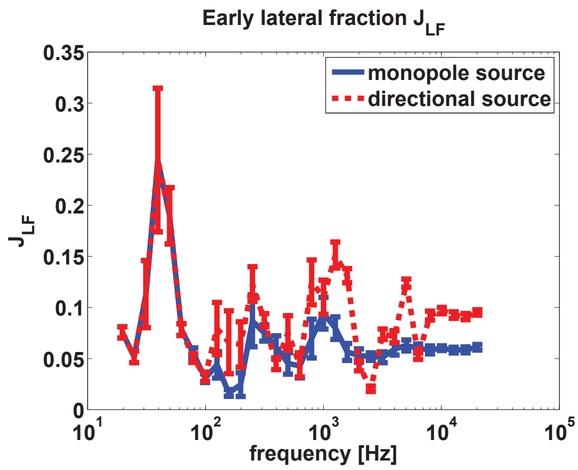

Figure 6: Early lateral fraction results using a monopole and a radiation pattern of a guitar.

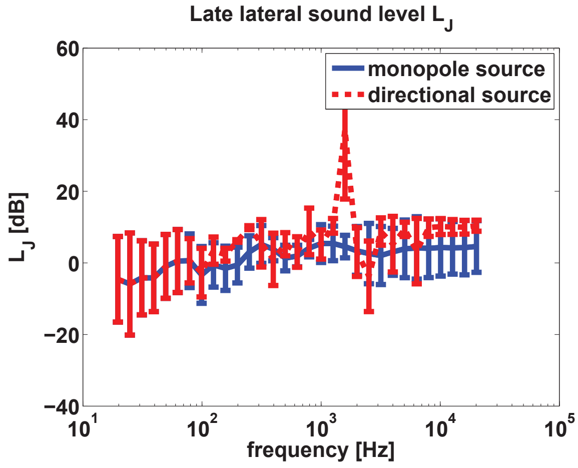

Figure 7: Late lateral sound level results using a monopole and a radiation pattern of a guitar.

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