Synthesis of Room Impulse Responses for Arbitrary Source Directivities using Spherical Harmonic Decomposition

Martin Kunkemöller, Pascal Dietrich, Martin Pollow, Michael Vorländer
Institute of Technical Acoustics, RWTH Aachen Universtity, Email: martin.kunkemoeller@rwth-aachen.de

Motivation

Room impulse response measurements are usually performed with approximately omni-directional radiating sources. The measurement result can be used to derive room acoustic parameters or to auralize sources in the measured room by convolution with a dry signal. However every real acoustic source has a distinct frequency dependent radiation pattern, which is to some extent responsible for the perceived characteristics of the source.

This motivates an approach that is capable of obtaining room impulse responses for specific radiation patterns by superposing measurement results of a well-known sound source with different orientations. In this contribution we discuss the methodology and some experimental results.

Method

The proposed method can be divided into two parts, measurement and synthesis. During the measurement-part multiple impulse responses of always diverse but known sources are measured. These signals will be superposed later on, regarding the room as approximately linear and time-invariant (LTI). This assumption holds for most acoustical systems within certain limits [7].

The diverse source patterns are obtained using a spherical loudspeaker array. The impulse response of the single drivers $h(t)$ or its frequency representation $H(\omega)$[1][2] are measured by using exponentially swept sines (sweeps) as excitation [1]. Thereby, we employ a time saving approach that uses interleaved excitation signals allowing several loudspeaker chassis to run at the same time [3].

The array is rotated in the horizontal plane by a computerized device allowing us to an increase the number of diverse source patterns. Figure 1 illustrates the approach schematically for an array of three loudspeakers: Each driver is excited subsequently in two orientations leading to six diverse radiation patterns.

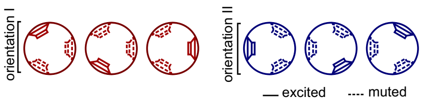

Abbildung 1: Superposition of several, differently oriented loudspeakers chassis.

[1]The two representations have a fixed mathematical relationship. Hence they are used as synonyms in this work.
[2]For a better readability complex values are used without subscripts in this contribution.

Synthesis of Target Responses

In order to approximate the impulse response $h_\mathrm{T}(t)$ or $H_\mathrm{T}(\omega)$ of an arbitrary target radiation pattern, complex and frequency dependent weighting factors w_l are determined to superpose a set of L measurements $H_l(\omega)$.

$$H_\mathrm{T}(\omega) \approx \sum_{l=1}^{L} H_l(\omega) \cdot w_l. \tag{1}$$

The radiation characteristics of an acoustic source can be described by the directivity factor Γ [4]:

$$\Gamma(\theta, \phi) := \frac{P(r, \theta, \phi)}{P(r, \theta_0, \phi_0)}. \tag{2}$$

This gives the complex ratio between the pressure P in any radiation angle (θ, ϕ) and in a reference direction(θ_0, ϕ_0). Thereby (r, θ, ϕ) are the coordinates of the common spherical coordinate system. In general, P and Γ are complex and frequency dependent.

The directivity factor can be decomposed into spherical harmonics [5]

$$\Gamma(\theta, \phi) = \sum_{n=0}^{\infty} \sum_{m=-n}^{m} \hat{\Gamma}_{n,m} \cdot Y_n^m(\theta, \phi), \tag{3}$$

where $\hat{\Gamma}_{n,m}$ are frequency dependent and complex valued coefficients, and Y_n^m are spherical harmonics. A detailed work on characterizing radiation patterns using spherical harmonics is given by Zotter [6].

The radiation pattern of a real source has a finite roughness over the surface. Therefore its characterization in the spherical domain can be limited to a maximum order N_max, and the spherical harmonic coefficients can be summarized in a column vector [6]:

$$\hat{\mathbf{\Gamma}} = \left[\hat{\Gamma}_{n,m}\right] \tag{4}$$

where $0 \leq n \leq N_\mathrm{max}$ and $-n \leq m \leq n$.

Each of the above-mentioned L measured impulse responses corresponds to a certain source radiation pattern, which can be also written in such a vector $\hat{\mathbf{d}}_l$.

Let $\hat{\mathbf{\Gamma}}_T$ be the radiation pattern of the target to be synthesized, and we can formulate by analogy with eq. (1):

$$\hat{\mathbf{\Gamma}}_T \approx \sum_{l=1}^{L} \hat{\mathbf{d}}_l \cdot w_l. \tag{5}$$

Summarizing the vectors $\hat{\mathbf{d}}_l$ in a matrix, we can write this equation as

$$\hat{\mathbf{\Gamma}}_T \approx \left[\hat{\mathbf{d}}_1 \quad \ldots \quad \hat{\mathbf{d}}_L\right] \cdot \left[w_1 \ldots w_L\right]^T = \hat{\mathbf{D}} \cdot \mathbf{w}, \qquad (6)$$

leading to an inverse problem, that can be solved by using the Moore-Penrose pseudo inverse $\hat{\mathbf{D}}^+$ [2]:

$$\mathbf{w} = \left(\hat{\mathbf{D}}^{\mathbf{H}}\, \hat{\mathbf{D}}\right)^{-1} \hat{\mathbf{D}}^{\mathbf{H}} \cdot \hat{\mathbf{\Gamma}}_T = \hat{\mathbf{D}}^+ \cdot \hat{\mathbf{\Gamma}}_T. \qquad (7)$$

In order to suppress the impact of noise and measurement uncertainties on the synthesis result, Tichonov regularization method is applied [2].

Experiments

The proposed method was evaluated by a comparative experiment in a small lecturing hall[3]. Two main measurements were conducted: the one with the spherical loudspeaker array as descrived above and the other with a loudspeaker of known radiation pattern, which was also used as target response for synthesis. Figure 3 shows

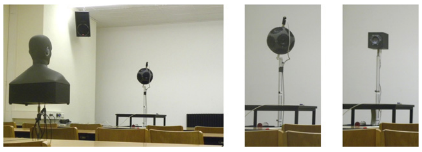

Abbildung 2: Setup for comparative measurements.

the measurement with the real source and the synthesis result in the time domain, the lower image zooms into the range of the first reflections in the room impulse response. The results show a good agreement.

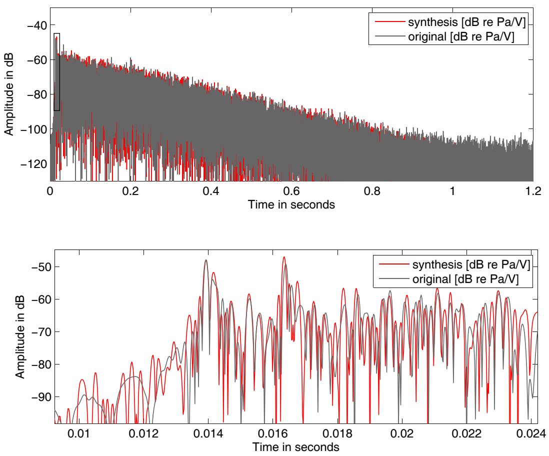

Abbildung 3: Measured and synthesized impulse response.

The correlation-coefficient measures the compliance of two signals. Figure 4 shows the correlation-coefficient of measured and synthesized impulse responses over frequency, at different numbers of orientations applied during the measurement part. 1 orientation represents 12 source patterns, 20 orientations represent 240 patterns.

[3]Lecturing hall in the Institute of Technical Acoustics with a reverberation time of approx. 0.9 seconds at mid frequencies.

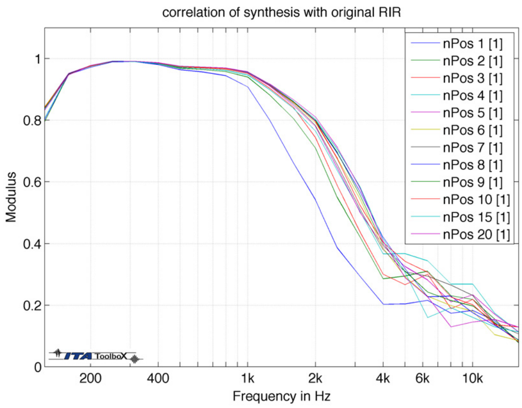

Abbildung 4: Correlation coefficient in frequency domain for different number of orientations of the loudspeaker array.

As can be seen, the correlation coefficient is close to 1 for frequencies below 3 kHz, which corresponds to the mid-tone-speaker's frequency range. Therefore in this range the synthesized room impulse responses are in good agreement with the originally measured room impulse responses using the target source. The correlation is improving by the number of sources applied for synthesis.

Conclusion

We have proposed a measurement method for synthesizing room impulse responses of arbitrary source radiation pattern. The method was validated in a small lecture hall using a 12-channel mid-tone-dodecahedron spherical loudspeaker array and a automatically adjustable orientation to increase the number of different radiation patterns. The results obtained by the synthesis were compared to measurements with a source which was also used as target for the synthesis.

Literatur

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