Measurement of Room Impulse Responses with Controllable Directivity

Johannes Klein, Martin Pollow, Ander Perez, Michael Vorländer
Institute of Technical Acoustics, RWTH Aachen University, Aachen, Germany
johannes.klein@akustik.rwth-aachen.de

Introduction

Room impulse responses include the directivity of the sources and receivers that are used for their measurement. Traditionally, this implies an omni-directional directivity which is not desirable for many applications. The evaluation of rooms regarding specific sources, the analysis of specific transfer paths and realistic auralizations require a controllable source and receiver directivity. Nowadays, the application of microphone arrays as receivers is common practice. An efficient way to synthesize the room impulse response for a controllable source directivity and the arising challenges are presented in this work.

Room Impulse Response Synthesis

The synthesis of room impulse responses requires three different measurements: the measurement of the target source (cf. [1]) and measurement source directivity as well as the measurement of room impulse responses with the measurement source.

Room Impulse Response Measurement

A large number of room impulse measurements is needed for the synthesis. All room impulse responses are obtained with the measurement source pointing in different physical orientations in elevation and azimuth. Time variances become a problem as a result of the long measurement durations (cf. Figure 1).

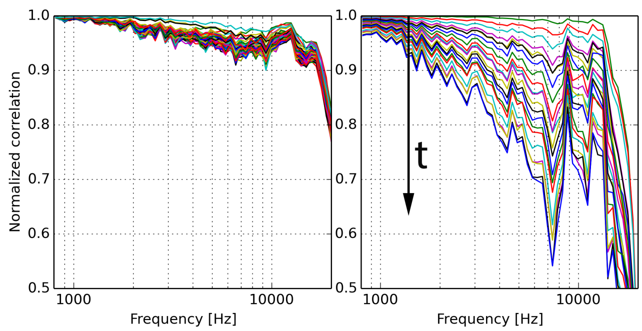

Figure 1: Correlation of the first measurement result with further room impulse responses measured over time. Left: room with a small volume; Right: room with a large volume.

Synthesis Method

The directivity of the two measured sources is decomposed into spherical harmonics and stored in vectorized form for every frequency. Here, all operations are performed exemplary for one frequency to enhance the readability. The decomposed directivity of the target source is denoted by $\hat{\mathbf{t}}$. The decomposed directivity of the measurement source is rotated in all physical orientations used during the room impulse response measurement by applying the Wigner-D rotation [2]. The resulting vectors are aggregated in the matrix $\hat{\mathbf{D}}$. The projection

$$\hat{\mathbf{t}} = \hat{\mathbf{D}} \cdot \mathbf{g} \tag{1}$$

using a weighting vector $\mathbf{g}$ can be inverted using a generalized inversion to yield

$$\mathbf{g} = \hat{\mathbf{D}}^{+} \cdot \hat{\mathbf{t}}. \tag{2}$$

The complex value of the synthesized transfer function

$$\mathrm{h_t} = \mathbf{h} \cdot \mathbf{g} \tag{3}$$

is derived by superposing the values of the measured transfer functions $\mathbf{h}$ with the weights for the respective orientations derived in Eq. (2) (cf. [3]).

Measurement Source

The synthesis weights in Eq. (2) are derived from spherical harmonic decomposed functions. Only orders of $\hat{\mathbf{t}}$ that contain a reasonable magnitude in $\hat{\mathbf{D}}$ can be synthesized. The magnitude contained in the orders depends on the transducer aperture (cf. Figure 2 and [4]). The apertures of traditional measurement sources are not optimized for this application. A new measurement source was developed to account for this and to speed up the room impulse measurements by using multiple channels (cf. [5]). 28 Transducers of three different sizes are placed on a spherical body of a 0.2 m radius. The resulting squared magnitudes are depicted in Figure 2.

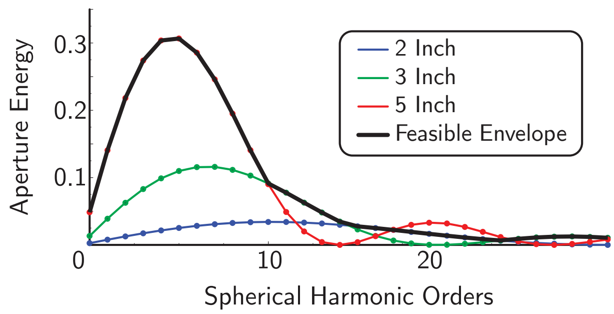

Figure 2: Squared magnitude of the spherical harmonics decomposed aperture functions of the three transducer types on the measurement source with a radius of 0.2 m.

A simple azimuth rotation of the source to 24 positions points the transducers in the orientations of a Gaussian sampling strategy of the order 11 requiring 672 room impulse measurements. One elevation tilt and a rotation to

48 azimuth positions in both elevations yields an order of 23 requiring 2688 room impulse measurements. Figure 3 shows the optimized measurement source.

Figure 3: Optimized measurement source with frame construction.

Directivity Measurement

The directivity of the measurement source is measured in a semi-anechoic chamber. The kr-limit (cf. [6])

$$n_{\max} = \lfloor k_{\max} \cdot r_{\text{sphere}} \rfloor = \left\lfloor \frac{2\pi \cdot f_{\max}}{c_0} \cdot r_{\text{sphere}} \right\rfloor \quad (4)$$

yields an estimated maximum order of 81 that can be radiated by the source at a frequency of 22 kHz. The directivity of each transducer is measured at 6889 measurement points distributed according to a Gaussian sampling strategy of an order of 82. In a semi-anechoic chamber it is only possible to measure the upper hemisphere of the directivity. To measure the lower hemisphere the measurement source has to be tilted by 180° (cf. Figure 4).

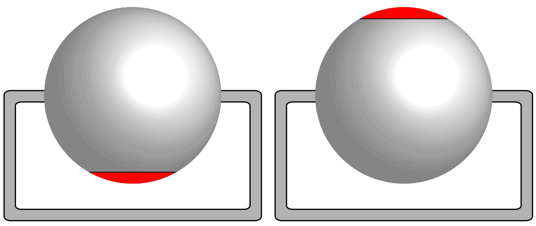

Figure 4: Illustration of the orientation of a transducer on the sphere during the measurement of the upper (left) and the lower (right) hemisphere of its directivity in a semi-anechoic chamber.

The maximum measured squared magnitude

$$E_{\hat{\mathrm{p}}}(n) = \max_{-n \leq m \leq n} |\hat{p}_n^m(r)|^2 \quad (5)$$

of the spherical harmonics decomposed source directivity is depicted in Figure 5. A range of orders higher than predicted by the kr-limit contains a considerable maximum squared magnitude starting at 1 kHz and exceeding the 82nd order at 7 kHz. This effect is probably caused by the virtual enlargement of the source due to reflections at the frame construction (cf. Eq. (4)). Aliasing occurs for all frequencies above 7 kHz. The orders up to 23 which are of interest for the synthesis are affected by the aliasing only for fairly high frequencies.

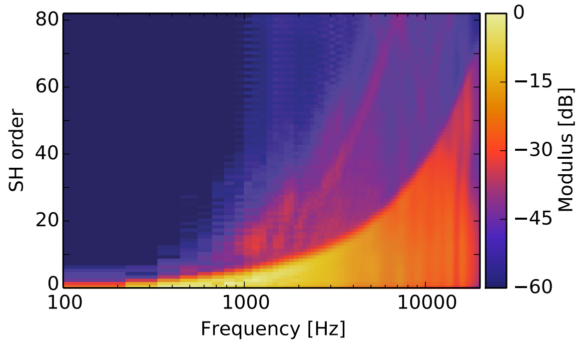

Figure 5: Measured maximum squared magnitude in every oder of the directivity of all transducers of the measurement source over the frequency (cf. Eq. (5)), normalized to the absolute maximum.

The directivity of a single transducer is shown in Figure 6. The measurement shows artifacts for elevation angles below 90°. To measure the lower hemisphere of the directivity the source is tilted by 180° (cf. Figure 4). The position of the transducer relative to the frame construction is changed and causes the artifacts. Since the measured directivity is used in Eq. (2) the artifacts only impair the synthesis because they are not present during the room impulse measurements. A symmetrical frame construction would guarantee the same artifacts during the directivity and the room impulse measurement.

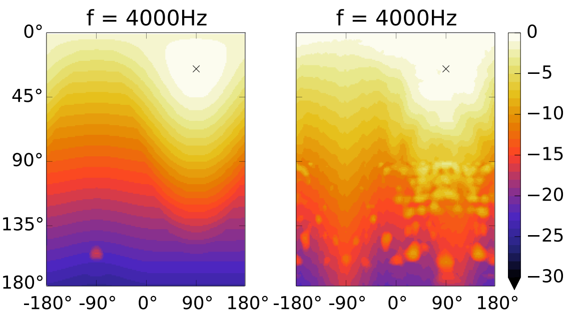

Figure 6: Amplitude of the sound pressure radiated by a 3 inch transducer on the measurement source at 4 kHz in azimuth (x-axis) and elevation (y-axis), normalized to the absolute maximum. Left: simulation; Right: measurement.

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