1aAAa8. Including directivity patterns in room acoustical measurements

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Room acoustical measurements according to ISO 3382 require source and receiver to be of omnidirectional sensitivity. Therefore, radiation patterns of natural sources and receivers (although audible) are not accounted for when using the obtained room impulse responses (RIRs) for room acoustic analysis or even auralization. In order to include this spatial information in the RIR, it is necessary to measure the RIR for each pair of radiation patterns of source and receiver. This could be done by electronic beamforming during the measurement using array systems or by mechanical modification of the transducer (as e.g. a dummy-head with its corpus). In this contribution an alternative approach is shown, using the superposition of a set of sequential measurements done with a spherical sound source. At the cost of longer measurement times the obtained data can be used universally to synthesize RIRs of arbitrary directivity up to a certain maximal spatial resolution, as long as the room is considered as a linear and time-invariant system during the measurement. Based on this representation of the RIR more advanced spatial room acoustic analysis accounting for arbitrary sets of source and receiver directivity becomes possible.
**MOTIVATION**

Room acoustical measurements are usually performed in accordance to ISO 3382 in order to objectively evaluate the acoustics of rooms. Fulfilling this norm provides comparability of the obtained results. Among other things the norm requires sender and receiver to have both an omnidirectional radiation pattern, thus yielding identical excitation of the room independent of their orientation. Real sources, however, usually possess an increasingly pronounced directivity pattern with rising frequency. For the ideally omnidirectional sources used in measurements this deviation contributes to the uncertainties in the obtained results [1].

When using the results of the measurement for auralization or for the determination of room acoustical parameters the directivity patterns of source and receiver are intrinsically tied to the result. Thus, it is impossible to separate or evaluate the effect of different directivity patterns of source and receiver if the measurement was performed in accordance to ISO 3382.

In recent years several studies were conducted to evaluate the influence of directive sound sources and receivers on the perceived room acoustics. Otondo and Rindel performed listening tests on real sources in rooms and concluded that specific directivity patterns of musical instruments differ significantly from omnidirectional radiation with a well audible effect [2]. Room acoustical simulations showed that the auralization of rooms can be enhanced by the inclusion of the directivity patterns of the real sources [3]. Recent studies suggest, that the influence of the directivity on the room impulse response is not only limited to the early temporal part, but also has noticeable influence on the late part of impulse response after multiple reflections [4, 5].

Several approaches are possible to obtain the room impulse response for specific directivity patterns. The directivity pattern can be created by mechanical modifications of the transducers, such as by modification of the radiating parts [6] or by mounting the transducer onto mechanical scatterers, a method that is commonly used in binaural technologies with the use of artificial heads [7]. Another approach is to use array based transducers with individual multi-channel excitation for directive sound synthesis [8, 9, 10, 11] or on the receiver side using beamforming approaches with spherical microphone arrays [12, 13].

In this paper a method on how to perform room acoustical measurements with an exchangeable directivity pattern is introduced. Using a specialized sound source for sequential measurements and linear superposition in the post-processing stage, the room impulse response and the derived room acoustical parameters can be calculated for the desired directivity patterns of source and receiver.

**ROOM IMPULSE RESPONSE SYNTHESIS THROUGH SUPERPOSITION**

Spherical loudspeakers used for state-of-the-art room acoustical measurements usually consist of several transducers mounted in a (more or less) spherical chassis with a regular placement of their membranes. By unique excitation of all membranes, a fairly uniform radiation pattern can be achieved for low and medium frequencies.

Alternatively the radiation pattern of each single transducer in the spherical loudspeaker can be measured and summed up, yielding also to a uniform radiation pattern. As the radiation impedance differs, however, the resulting radiation pattern will differ from the pattern of simultaneous excitation of all membranes. Introducing a complex weighting factor for each transducer instead of using single-channel uniform excitation allows to form various directivity patterns by superposition. Considering the room as a linear and time-invariant system, also the room impulse responses can be superposed in the same way as the radiation patterns. The complex weighting factors for the superposition thus equal the superposition factors for the room impulse response, as long as the whole system is linear and time-invariant.
CALCULATION IN THE SPHERICAL HARMONIC DOMAIN

In order to derive the superposition factors, it is advantageous to decompose the directivities in a suitable vector base. Using a two-dimensional Fourier transform on the unit sphere, each possible physical directivity pattern can be expressed by a sum of Spherical Harmonics (SH), which regard an orthonormal base for square-integrable spherical functions [14]. A main advantage of this approach is that directivity data of different spatial sampling grids can be combined as the calculation is performed with the spatially continuous SH base functions. Furthermore, the inversion algorithm can be modified with respect to the spatial change of the functions, as all Spherical Harmonic base functions of constant order constitute a complete set of functions with a certain spatial change. SH-order-dependent algorithms, such as the order-dependent Tikhonov regularization as used in the examples of this article, allow to discriminate the parts of different spatial change of a given function.

By spatial sampling of the SH base functions the problem is discretized and can be solved with methods from linear algebra. The information obtained for a set of measurement points of constant radial distance from the radiating object is transformed to a limited set of SH coefficients by inversion of the linear system. The generally semi-infinitive set of Spherical Harmonics used for the calculation is limited to a number, which is suitable for the frequencies under consideration and the employed spatial sampling of the given data. A sufficiently high sampling resolution is required for a fixed maximum order of Spherical Harmonics to avoid aliasing errors in the process of transformation to the SH-domain [15].

The reconstruction of the spatial signal can then be done by weighting all Spherical Harmonic base functions with the corresponding SH coefficients and summing up the results.

DESIGN OF THE MEASUREMENT DEVICE

The goal for designing an optimal measurement source for room impulse responses with arbitrary directivity patterns is the synthesis of all possible directivity patterns up to a certain spatial variation. Using the concept of a decomposition into SH-coefficients allows to set rules for the computation. The radiation pattern of the single transducers should yield a distribution of energy in all possible SH coefficients up to a maximum SH-order the source should be able to cover.

Because of the physical size of the membranes and the confined space, it is difficult to obtain a high spatial resolution with spherical loudspeakers with simultaneous playback. Assuming time-invariant behavior of the system, the spatial resolution can be enhanced by subsequent measurements with different orientations of the transducers.

The easiest mechanical implementation for the variation of the membrane orientation is the rotation around the vertical axis of the spherical loudspeaker. Doing so the sampling grid of the loudspeaker can be designed to fully cover the elevation of the sampling points, while the azimuthal orientation are adjusted by placing the measurement source on a turn-table that can be oriented to arbitrary angles.

Choosing the Gaussian sampling schema as an efficient spatial sampling with points on identical elevation angles for azimuthal angles, the placement of the membranes can be determined. The diameter of the chassis is chosen to be 40 cm as a compromise of suitable size for sufficient volume in the low frequency range and manageable weight and size.

A single membrane in a spherical chassis can be modeled analytically by a radially vibrating spherical cap. The surface velocity on the surface of the chassis can thus be defined as a weighted sum of aperture functions for each membrane [9]. Depending on the ratio between membrane size and chassis size, a specific order dependent aperture energy distribution of the velocity on the surface of the spherical chassis can be observed. As the resulting radiation pattern is a
multiplication of this SH-decomposed surface velocity function with terms of spherical Hankel functions, the design criteria is to ensure sufficient energy distribution in all SH-orders in the range of interest. Each membrane size has some characteristic notches in the aperture function, so that the sizes of the used membrane have to be chosen to provide significant energy in all SH orders. The notches can be seen e.g. in Fig. 1 at orders of around 14 for the large membrane type where the energy has to be provided by the smaller membranes. The useable energy for directivity synthesis is marked with a black solid line in this plot. The high orders of the large membrane are disregarded as they usually occur at high frequencies out of the operating range of this type of transducer. The total distribution of the membranes in the sphere and the mounting situation on the turn-table is depicted in Fig. 2.

![Figure 1: Aperture energy of the three different membrane types used. The feasible envelope of the membranes in their operating frequency range is marked as black line.](image1.png)

**Figure 1:** Aperture energy of the three different membrane types used. The feasible envelope of the membranes in their operating frequency range is marked as black line.

**Prototype of the Spherical Loudspeaker**

The measurement device constructed to fulfill the mentioned requirements consists of a spherical chassis of 40 cm diameter, placed on a computerized turntable for the azimuthal variation of the device. The device can either be used in a fixed elevation for the coverage of a Gaussian sampling of order 11, or with two different elevations, for an approximative Gaussian sampling of order 23 with the cost of longer measurement time. The prototype of the spherical loudspeaker can be seen in Fig 3.

After the construction of the spherical loudspeaker, the radiation pattern of the individual transducers can be measured. The simulation data of the spherical cap model (as used in the design phase) can thus be replaced by a more accurate measurement that also takes the individual sensitivity of the transducer and the mounting situation (such as the influence of the fixture) into account.

Using a specialized measurement equipment for spherical measurements as depicted in Fig 4 the directivity pattern of the device can me measured with high spatial resolution. A computerized arm holds a microphone in place and in conjunction with the turn-table below the spherical loudspeaker this measurement procedure yields high resolution sensitivity data of the device.

The spherical loudspeaker can then be used for the measurement of room impulse responses with arbitrary directivity. As time-invariance of the whole system during the measurement is critical, a main focus is put on a high speed measurement procedure. The study of the correlation between subsequently measured room impulse responses for a fixed sound source showed that “rooms can be assumed to be time-invariant for measurement periods of 60 minutes up to 90 minutes” if dealing with small or medium sized rooms [16]. By measuring the room re-
**Figure 3:** Prototype of the spherical loudspeaker

**Figure 4:** Measurement system for the directivities of the individually excited single membranes. Spherical loudspeaker mounted on a turn-table. Microphone mounted at the end of the arm (on the right)
spense for several transducers simultaneously using the optimized multiple exponential sweep measurement proposed by Dietrich this time constraint can be fulfilled [17], thus allowing the superposition approach for room impulse responses.

For larger rooms or rooms with a more complex thermic regulation the assumption of time-invariance will have to be proven with the help of the mentioned correlation analysis.

**EXAMPLE 1: SYNTHESIS OF NARROW BEAMS**

As a first example the measured directivity patterns of the spherical loudspeaker are superposed in order to create a narrow beam in arbitrary direction. For the inversion the classical Moore-Penrose pseudo-inverse and the order dependent Tikhonov regularization as suggested by Duraiswami is used [18].

The target directivity, the result of the inversion using the pseudo-inverse and the result for the Tikhonov regularization are plotted in Fig. 5, 6 and 7, respectively.

It can bee seen, that the inversion with the Moore-Penrose pseudo-inverse seems more accurate for high frequencies, whereas the Tikonov-regularized results yield smoother lobes for lower frequencies.

**EXAMPLE 2: SYNTHESIS OF HRTFs OF AN ARTIFICIAL HEAD**

As a more demanding target function the HRTFs for the right ear of a dummy head is used. Exploiting reciprocity it is possible to use a directive sound source to measure the transfer paths
for a sound receiver with specific directivity. The given target directivity is complex valued, thus representing the correct time delay of the HRTFs. The same inversion methods as in the previous example were used with the results depicted in Fig. 8, 9 and 10.

**Figure 8:** BEM-simulated set of HRTFs

**Figure 9:** Synthesis of a BEM-simulated set of HRTFs using pseudo-inverse

**Figure 10:** Synthesis of a BEM-simulated set of HRTFs using order-dependent Tikhonov regularization

**Conclusions and Outlook**

Directivity pattern of sound sources have to be assumed omnidirectional when measuring in accordance to ISO 3382, although they contribute significantly to the acoustics of rooms. In order to measure room impulse responses with the possibility of subsequent auralization and room acoustical analysis for arbitrary directivity a measurement setup was presented. It allows to obtain a set of room impulse responses that can be superposed to one room impulse response for
any arbitrary directivity pattern up to a certain order. With the prototype measurement source it is possible to superpose the single membrane radiation patterns and the resulting room impulse responses in order to obtain the room impulse response for any arbitrary target directivity. Important requirements for the superposition approach is linearity and time-invariance. Allowing the air volume in a room to settle for several minutes the variance of the system over time is diminished. For large concert halls the time-invariance has to be proven prior to performing new computations. This can be done by using a correlation analysis on a set of room impulse response measurements of a static sound source.

Ongoing work is conducted on the measurement of room impulse responses using a combination of both directive source and receiver. Combining the proposed loudspeaker array with a spherical microphone array the total transfer path for arbitrary directivity patterns of source and receiver in a room can be stated. This approach is expected to enhance the quality of room acoustical auralization and provide relevant data for possible alternative ways to define significant room acoustical parameters.

REFERENCES


