On the Application of Array Technology in Room Acoustics

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Introduction

An overview on the applications of a scalable spherical array in room acoustics is given. The measurement system enables a volumetric analysis of the sound field and a directional examination of the acoustical properties of the enclosure by principles of the Nearfield Acoustical Holography [1]. Based on an improved insight into the sound field, the method is prospectively capable to contribute to the bridging between classical room-acoustical measures and their percept, which is regarded as a main issue in current room acoustical research. Likewise, the presented spherical array yields a series of new measurement possibilities, as e.g., a volumetric modal analysis, a volumetric intensity probe or a plane wave decomposition of the sound field to analyze the staggering of reflections and wall properties. Although the performance of the system has been demonstrated in recent years, the spherical array processing is still at a developmental stage and thus sophisticated. On that account, current research aims to utilize the spherical array to full capacity as well as to improve its numerical and mechanical robustness. A developed system is likely to be adopted by the acoustical consultancy due to its mere advantage over the classical point-wise measurement method in terms of accuracy and simplification.
This contribution is confined to an overview on applications of spherical array processing in room acoustics. For further information on fundamentals and implementations, references are given throughout the text.

Applications

Many fields in acoustics use spherical array technology to record and to reproduce sound fields. An early work by Weinreich and Arnold [2] introduced the spherical array for an expansion of the sound field into spherical harmonics to capture the radiation of violins. This is an "exterior problem" which is typified by the fact that all sources are inside a delimiting sphere[1], beyond which the sound field is observed. In room acoustics, the interest lies on the sound field in the far field of sources (which includes the reflecting enclosure). Therewith, all sources are outside a delimiting sphere and an "inner problem" is formulated.
The solution of the "inner problem" is the reconstruction of the sound field inside a volume (delimited by a virtual sphere). The solution finds its first principles in the Divergence Theorem of Gauss which relates the flux of a flow field in a source free volume to the information of the field on the surface around the volume. There are two ways to depart to the solution. One evolves from the Kirchhoff Helmholtz Integral (the mathematical formulation of the Hygens Fresnel Principle) and a special Green Function for the spherical case, the second way follows the efficient principles of Fourier Analysis in time and space, which are generally subsumed under the somewhat misleading term Nearfield Acoustical Holography, and yields the solution directly from solving the wave equation using spherical coordinates [1].
The solution results (A) in a decomposition of the sound field in spherical harmonics for the angular dimensions. Considering practical application, the general processing steps are:

1. the recording of impulse responses of the sound field at a particular surface grid[2],
2. the transformation of each impulse responses into transfer functions by a Fourier Transform and
3. the decomposition of functions of frequency at the surface upon the sphere into spherical harmonics by Spherical Fourier Transform, which results in the spherical wave spectrum.

The solution of the radial dimension of the wave equation is (B) an expansion into spherical Bessel functions of first kind. To reconstruct (i.e., to extrapolate) spherical wave spectrum at another radius, the afore calculated complex coefficients, that represent the spherical wave spectrum at the origin of the spherical array, are multiplied by a quotient of spherical Bessel functions[3]. The total sound pressure at a point on an extrapolated radius is then calculated by applying the Inverse Spherical Fourier Transform and the Inverse Fourier Transform, respectively.
A scalable spherical array was built and applied in the experiments mentioned in this survey. The array is comparable to the system presented in [4], the current version however features two microphone arms to halve the measurement time or to enable the parallel measurement at two radii.

[1] Considering the "exterior problem", the radius of the measurement sphere is smaller or equal the delimiting sphere.

[2] The efficiency of the grid is for the most part determined by the number of sampling points at a given order of the spherical decomposition.

[3] This is true for open spheres and the pressure information at the surface. See [3] for further information.

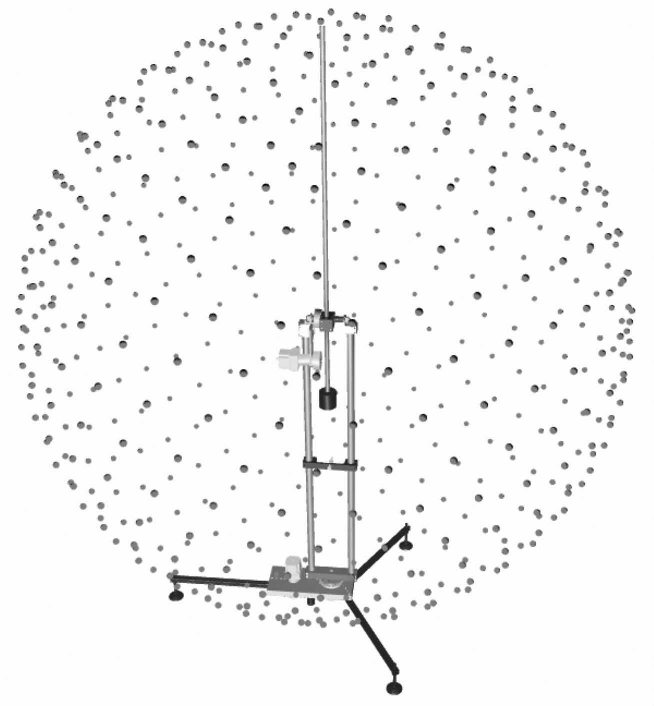

Figure 1: The virtual spherical array as applied in [4]. It allows via two rotatory degrees of freedom and an adjustable radius a scalable spatial sampling upon a sphere. The spherical arrangement of dots indicate the recording positions of a particular sampling grid.

Improving validity of acoustical measures

The research of room acoustics faces a clear inconsistency between classical room acoustical parameters and their psychological perception [5]. In recent years, regularly updated sets of psychoacoustical parameters were therefore developed. Their deduction from classical physical measures or from the mere energy structure of the impulse response is a difficult problem and is in general not solved.

The problem is approached via psychoacoustics by modelling the auditory scene analysis [6] or by the classical analysis of the physical properties of sound field. With respect to the latter, a primary problem of room acoustical measurement refers to the missing statistical basis when probing location-variant measures at loosely and sparsely distributed points in space. Most of these location-variant measures are calculated from the energy ratio of the time-partitioned impulse response (e.g., C80 - clarity) and their result should indicate a certain characteristic that is valid in a wider region (e.g., over the square of four seats in a concert hall) of the analyzed room. Line array measurements however revealed a strong fluctuation along small spatial variation [7]. This fine structure is (as opposed to the global variation of acoustical measures in a room) not perceived by the listener and attributed to the interference effects in the “early part” of the sound field. The improvement of the validity of classical acoustical measures is a central motivation for the presented method. In principle, the volumetric analysis allows for the observation of location-variant measures throughout a large volume and the identification of abnormalities. As suggested in [7], by calculating a mean of a particular room acoustical measure from the evaluated volume, a true, i.e., a value close to the perception is expected.

In our earlier works, the volumetric analysis was restrained by the robustness of the algorithm, a high computational effort and mechanical imprecision of the array. Recent improvements of the method are yet to analyze. Up-and-coming is the application of cardioid microphones in the spatial sampling by Melchior et al. [8]. Therewith the typical ill-condition in the radial solution of the wave equation (when using omnidirectional transducers) is avoided. Moreover, they introduced a coherence measure to evaluate the extrapolation performance and showed that a band-limited wave field is accurately calculated in the volume surrounded by the microphone array.

Modal Analysis

A similar problem of room acoustical measurement applies to the modal analysis of small rooms. Below the Schroeder Frequency [9], the sound-field shows a modal behaviour and is therefore non-isotropic. Although the spatial sampling on a tridimensional grid is suggested for the analysis of the low-frequency part of the sound field, the practical exercise can generally not afford such rather laborious procedure. The proposed volumetric analysis method of the sound field is capable to image room modes at arbitrary spatial scale and delivers accurate tridimensional holograms. This simplifies the measurement effort and moreover, as standing waves are characterized by a periodic structure, the analyzed volume yields a wave pattern that reiterates throughout the room.

The spherical array was applied in the modal analysis of several rectangular rooms. By solving the Helmholtz Equation to obtain the room modes of these rectangular rooms, analytically, a clear congruence with the standing wave structure of the particular volumetric measurement was found [4, 10].

Directional Analysis of the Sound Field

Spherical arrays are suited to capture directional impulse responses and thus to image the staggering of early reflections through their energy contributions and directions. The possibility to analyze the directional contributions of the sound-field is of great help for consultants and architects. Wall properties, as absorption and scattering, could be directionally identified, analyzed by means of their psychoacoustical impact and selectively altered to meet particular requirements. A directional analysis can be performed by a reconstruction of the intensity vector throughout the analyzed volume [11, 12] or by the calculation of the spatial density of wave amplitudes using a plane wave

decomposition of the sound-field [13].
In contrast to point-probes, the volumetric intensity analysis avoids the misinterpretation due to local interference. The computation of the volumetric intensity probe is based on a gradient method that is applied on an extrapolated lattice of pressure scalars.
In an experiment, the spherical array was applied to calculate the volumetric intensity of a simplified setup featuring one sound source and one reflection in an anechoic room [12]. The reconstructed intensity vectors were found to corrently indicate the directions of incidence.
The same experimental setup was used to perform a plane wave decomposition of the sound field by Thiergart [3]. In this work, a measurement at two radii with cardioid micorphones was performed to achieve a robust broad-band analysis. Moreover, the extraction of the transfer-function from plane waves was demonstrated. In this manner, access to the absorption properties of the enclosure is given, i.e., the spherical array can act as an "acoustical camera" of arbitrary resolution.

Conclusion

Based on the efficient principles of the Fourier Transform in time and space, a spherical array configuration provides new possibilities in the measurement of room acoustics. While the volumetric analysis sheds light on the non-isotropic "early" and low-frequent part of the sound field by the help of tridimensional probes of sound pressure and intensity, the plane wave decomposition of the sound field enables the directional analysis of reflection and their frequency-transfer. In several experiments, the excellence of the spherical array measurement was verified. Future research pursues the improvement of the array's mechanical and algorithmic robustness. Particular interest is directed towards regularization techniques that improve the robustness in plane wave decomposition [14, 15] and extrapolation. Furthermore, the spherical array is regarded as a tool to parameterize room acoustical properties and to deliver these parameters to simulation software tools, so that architectural alterations are conveniently simulated before being implemented. Therefore inversion, based on wave back propagation, is considered a suitable tool to extrapolate the sound field beyond the array including the enclosure. Using a planar array geometry, an account on inversion for the reconstruction of wall properties was adduced by Kuster et al. [16]. By this means, the directional analysis of the array might evolve from the current "telescope", by which we observe the waves that travel perpendicular to its surface, to a measurement system that can reconstruct a great portion of the sound field from a single array measurement.

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