Post-processing and center adjustment of measured directivity data of musical instruments

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Surrounding spherical microphone arrays can capture the radiation pattern of sound sources placed inside the array. Depending on the exact positioning of the sound source the obtained measurement results vary, as amplitude and phase differences arise due to the different traveling time of the radiated sound. Using the spherical harmonic decomposition of the sound field, it is noticeable that displaced sound sources need a much higher number of modal components for an accurate description. As surrounding spherical microphone arrays are severely limited in their spatial resolution correct centering is crucial for higher frequencies.
In practice, however, a precise alignment to the physical center of the array is impossible. With the help of re-alignment algorithms it is possible to virtually shift the sound source to the center of the array to allow a more accurate description in the spherical harmonic domain. Alternatively, a magnitude only approach can be employed, resulting in a more robust representation regarding incorrect centering in the array.
In this contribution different post-processing strategies are presented with the goal to provide directivity patterns of musical instruments for application in both measurement and simulation.

1 Introduction

This contribution gives an overview of different post-processing methods for directivity patterns as measured with a surrounding spherical microphone array. Whereas technical sound sources are usually well reproducible, natural sound sources are usually measured in all directions synchronously due to the non-repeatability of their excitation. Depending on the type of instruments the simplification to define a general frequency dependent directivity pattern which is independent of strength and style of playing is more or less accurate.

The goal is to create a data base for directivity of musical instruments for the use in room acoustical simulation software as well as for room impulse response measurements with respect to the directivity of the source. This contribution is based on data obtained with the measurement setup as described in Behler [1].

2 Motivation and applications

Directivities of natural sound sources are often neglected in auralization despite being of great perceptional significance in room acoustics [2]. However, it is possible to include the directivity of the sound sources in both room acoustical simulation software and specialized measurements for room impulse responses, with the cost of higher complexity. For measurements, e.g. specialized sound sources have to be employed [3, 4].

The required data interface for these different applications however varies, so that the recorded directivity is provided in a flexible way to suit all applications.

As some musical instruments also vary their acoustical radiation center (e.g. large woodwinds instruments), this can be included as well in the stored data in order to provide realistic effects, especially for real-time auralization of instruments in room acoustical software. One example is the CAVE-like environment at RWTH Aachen University, where the measured and processed directivity patterns are currently implemented in an enhanced version [5, 6].

2.1 Dynamic room acoustical simulation

The acoustical simulation software developed in the Institute of Technical Acoustics currently uses directivity magnitude data averaged in third band octaves [7]. This shows that some meaningful simplification and averaging has to be done to be able to include the directivity patterns of musical instruments in this software.

As fast access to the directivity data is crucial, a new file format named *OpenDAFF* was developed to fulfill the demands [8]. The spherical data hereby is sampled on an equiangular grid and can be accessed with the help of an efficient nearest-neighbor search to provide the directivity of approximate directions. While a spatial continuous storage is generally possible (with the help of suitable base functions such as spherical harmonics), for highest requirements regarding latency a nearest neighbor search with a high sampling density shows best performance.

2.2 Room impulse response measurements

A completely different approach is the determination of room impulse responses with respect to directivities by acoustical measurements. Specially designed spherical sound sources are used for measuring a set of RIRs that can be superposed later on to the directivity pattern of interest [3, 4].

The demands for this approach are significantly higher. While still being required of averaging the directivities for specific frequencies, for this methodology a complex directivity pattern for each frequency is preferable to an averaged directivity pattern over a certain frequency range. Furthermore it is beneficial to gain a representation of the directivity patterns that has a limited spatial variation, that means is reduced in the number of required spherical harmonics coefficients. As spatial displacement (i.e. a misaligned source) leads to these higher orders, a subsequent re-alignment can enhance the results for this method, as shown later in this paper.

3 Definition of directivity

When speaking of the directivity of an instrument, the question arises whether or not taking surrounding obstacles in vicinity of the instrument into account. The scattering and diffraction from neighboring objects — most notably the body of the musician itself — changes the radiation pattern significantly. Also the usually strong ground floor reflection clearly has an impact due to interference of the waves.

As one of the usage for the directivity data was a measurement method for room acoustical parameters with arbitrary but given source directivities, the ground reflection had to be excluded from the data. The musician, however, is in symbiosis with the musical instrument regarded as the sound source that radiates with a specific frequency dependent directivity pattern. The directivity pattern is defined as the radiation from this symbiosis hovering in the acoustical free space, resulting in data that can be used in both simulation and measurement methods.[1]

4 Classification of the instruments

The character of the directivity of musical instruments depends greatly on the type of musical instrument. Whereas some instruments remain static while playing, others change their geometry, e.g. by the opening of holes or flaps. It can be noticed that the directivity of instruments with a static geometry can usually be well approximated with a spherical function over frequency. This is an important fact as this means the use of tone identification is not necessary for precise inclusion of directivities for auralization.

Musical instruments with a non-static geometry, on the other hand, usually posses tone dependent (i.e. for woodwind instruments fingering dependent) directivity patterns. Modal radiators such as the strings are also regarded as non-static and do possess a complicated directivity pattern. Studies with saxophones show that the sound radiation varies with the played tone and show correlation with the other tones in the same register [10, 11]. As some tones can be played in different fingerings, even pitch detection methods does not suffice to supply a correct frequency dependent radiation pattern for these types of instruments.

5 Data extraction

In order to extract a compact data set from the recordings different approaches can be taken, shown as follows.

5.1 Peak extraction

All relevant information of tonal instruments can be extracted from the peak values of the spectral lines. As musical instruments radiate usually at their fundamental frequency and a set of higher harmonics, the peak values at these discrete sets of frequencies is sufficient to describe the characteristic of a specific instrument. Hereby the phase transition in the resonance peaks has to be taken into account to be able to extract the correct phase relations between the microphones. A suitable window can be applied to avoid leakage while extracting the steady part of the tone.

The advantage of this approach is the physically appropriate evaluation of the sound pressure including phase differences between the microphones. These phase shifts are caused partly by the deviation of the traveling time to the different microphones. It is also important for acoustic center alignment methods to know the complex spectral behavior of the radiating source.

For complex radiation patterns at higher frequencies, however, the spatial resolution is too low to correctly capture the radiation pattern and spatial aliasing occurs. As higher spherical harmonic orders are required to represent displaced sources, a well aligned source can lower the error due to spatial aliasing. Using magnitude values instead of peak values no phase shift is created from de-centered sources, thus avoiding aliasing errors due to displacement. However, by taking the magnitudes also higher orders can be introduced, as can be seen by the perfect dipole whose magnitude need higher orders than the complex representation with a spherical harmonic order of one.

5.2 Averaging data

For many applications the average approach is most sufficient. Normalizing to one recorded direction the level differences on the other microphones can be averaged. Hereby, the phases are neglected, so this method resembles an energetic averaging approach, creating data that is suitable for most room acoustical simulation software using statistical methods. This has the advantage of relatively small variances for small deviations in the placement of the radiating source.

A possibility to enhance the perceptional effect is exploiting the effect of auditory masking, as mentioned by Zotter [12]. Hereby only the audible parts are included in the directivity pattern and any spatial variation below a certain threshold is not considered. This is expected to enhance the perceptional impression of the averaged musical instrument directivity.

Alternative to the processing in the frequency domain, it is also possible to process the data in time domain, either sample by sample or in blocks to average the radiation in specific time frames. Suitable filters can be applied to these blocks to evaluate the temporal behavior of the directivity in a certain frequency band. Time domain processing is useful for either data visualization or simulation of dynamically changing sound sources as they were measured (e.g. due to movement).

6 Source re-alignment

Depending on the location of the musical instruments during the recording the received signal on the microphones of the spherical microphone array varies. Due to the distance decay of the radiated sound field and the more compact representation in the spherical harmonic domain the primary goal is to align the sound source with the geometrical center of the spherical array.

In practice, however, it is impossible to align a sound source perfectly to the center of the array. Many types of musical instruments do radiate from larger structures. The woodwind instruments for example radiate by their hole openings and the string instruments use the whole body of the instruments for radiation. The simple model of radiation originating on a single point does not hold here [13].

However, other instrument types can be regarded as having a single spot where sound is radiated (e.g. brass instruments). With these instruments the relative phase relation observed on the different microphones can be used to trace down the true origin of the radiated sound.

Several algorithms were reported in literature to perform that re-alignment, with a comparison of different algorithms given in [14].

6.1 Alignment of complex pressure values

Complex data extracted from the measurement data by peak extraction is severely affected by a misaligned acousti-

[1] Some studies excite the musical instruments mechanically to evaluate their properties. While mechanical excitation has the charm of repeatability, this data needs to be modified before use to add the impact of diffraction and scattering from the musician for directivity analysis, cf. e.g. [9].

cal center. Depending on the frequency even small displacements can require a much higher number of spherical harmonics.

A compact representation of the directivity in terms of spherical harmonics coefficients is very desirable as the used measurement devices are limited in measuring RIRs of limited maximum spherical harmonic order [3, 4].

6.2 Alignment of sound pressure level

If working with levels or absolute values (e.g. as a result of averaging) the effects of displaced sound sources are not as severe. Of course, no phase shift occurs, just the magnitudes decay smoothly. For reasonable small displacements from the geometrical center of the array this results in moderate level shifts.

To give an example: recording an instrument with source within a sphere of a diameter of one meter in the array built at ITA with a diameter of 4.20 m the maximum level differences between the strongest and weakest direction due to the decay of the spherical wave is less than 5 dB.

6.3 Example: Alignment of complex pressure values of a trumpet

In Figure 1 the placement of the musician is depicted with perspective photographs for the case of the trumpet. A white cross marks the axis of the geometrical center of the array from two directions. It can be seen that the expected sound source can be assumed to be located further to the front than the marks suggest.

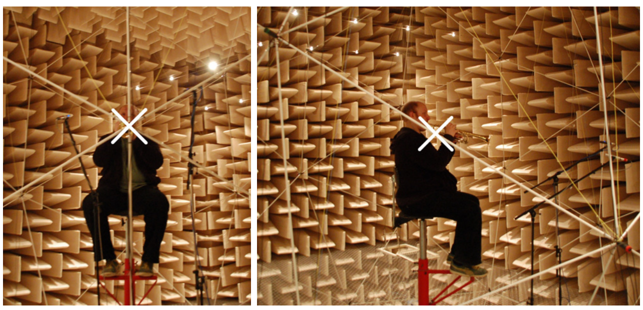

Figure 1: Perspective photos of the recording with geometric center of the spherical array marked with a white cross, cf. [14]

Analyzing the radiation at the 32 microphones and obtaining an interpolated result, the resulting continuous radiation is depicted in Figure 2. Hereby, the discrete values on the microphones are plotted together with its interpolated version using spherical harmonic decomposition. The amplitude is represented as radius, with the phase information encoded as color. The musician is facing the positive x-axis.

It can be clearly seen that the deviation of the acoustical center from the geometrical center yields a continuous phase displacement on the sphere, due to the differing traveling path length of the acoustical wave. Using non-linear optimization algorithms and compensation of both level and phase differences leads to the re-aligned result, depicted in Figure 3. All directions now in-phase values, indicating that the radiated acoustical wave arrives now at the same time at all microphones.

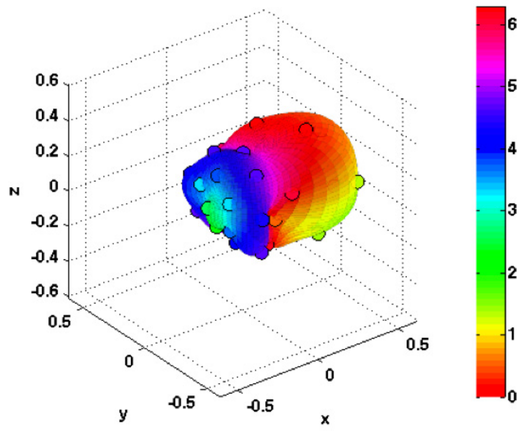

Figure 2: Radiation of a trumpet for a fundamental frequency of 440 Hz without re-alignment, amplitude depicted as radius, phase encoded as color information

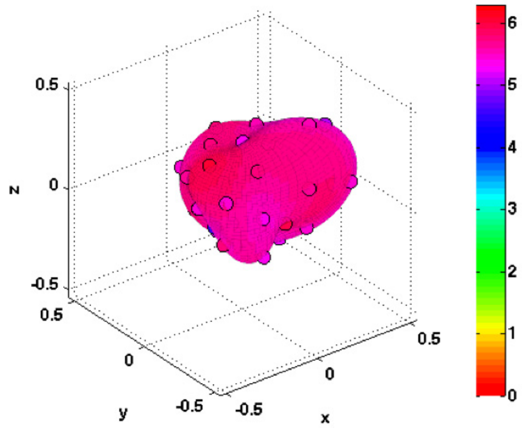

Figure 3: Radiation of a trumpet as in Figure 2, alined using an optimization algorithm (displacement of dx = 35 cm, dy = -2 cm, dz = -7 cm)

7 Conclusion

The recordings made with a spherical microphone array were post-processed to deliver useable directivity data for the use in room acoustical simulation software and acoustical measurement methods. Depending on the type of instrument the simplification of defining a frequency dependent directivity pattern independent of played pitch and style and strength of playing deviates more or less from the real directivities encountered at the recording.

As some of the applications require complex directivity patterns, while others suffice with averaged (magnitude only) information, different formats were extracted to deliver data to all possible use cases. However, especially the complex data vary significantly with the location of the measured instruments. To gain a compact representation in terms of spherical harmonic coefficients, re-alignment algorithms can be employed.

The goal of this study is to set the base for an enhanced auralization of both simulated and measured room impulse responses with respect to arbitrary directivity patterns.

Acknowledgments

The authors thank the Audio Communication Group at TU Berlin and the Research Group in Architectural Acoustics at Universidad Politécnica de Madrid for performing the directivity recordings in cooperate projects. Furthermore we thank everyone involved in the recording sessions.

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