Holographic loudspeaker measurement based on near field scanning

Christian Bellmann[1], Wolfgang Klippel[1], Daniel Knobloch[1]

[1] *Klippel GmbH, 01309 Dresden, E-Mail:info@klippel.de*

Introduction

Improving sound radiation characteristics of studio monitors, consumer electronics like laptops, smartphones or other personal audio devices, imposes an increasing demand for 3D near field data. In addition, for professional audio systems, 3D far field data of highest accuracy is the base for 3D sound field simulation software like EASE. As well, the economic factors like measurement time, costs and spatial requirement provide an incentive for seeking new methods for 3D directivity measurement.

Conventional Directivity Measurement

Traditionally, directivity is measured in the far field under anechoic conditions. This is done at a high cost, with substantial remaining inaccuracies: Special measurement rooms satisfy the required conditions in a limited bandwidth, above a cut-off frequency (~100Hz). Below the cut-off frequency, the absorption of the room is insufficient.

As an alternative, far field measurements can be performed under simulated free field condition, without the need of an expensive anechoic room. Due to time windowing, the room reflections are separated from the direct sound. However applying this method, the frequency band is limited (typically f>500Hz) by the time difference between direct sound and the first reflection.

Furthermore, measuring large devices requires a large measurement distance, which may reach the room dimensions. Measuring at large distance brings up another problem. Accurate phase measurement, especially for high frequencies, requires controlled climate conditions to ensure a homogeneous temperature field. For example a temperature deviation of just 2 Kelvin causes a phase shift of 180° (λ/2) at f=10kHz in 5m distance.

To determine a full set of directivity data with a high angular resolution, a huge number of measurement points is required. Performing a measurement with an angular resolution 2° requires 16200 point and long measurement times, as well.

Near field measurement

Measuring in the near field has several benefits compared to the far field measurement. Because of a high signal-to-noise-ratio (~20dB higher than far field) the measurement can be performed faster without the necessity of time averaging. In addition, direct sound has a high level compared to room reflections, reducing the requirements to the measurement ambience. The measurement can cope with some ambient noise. In addition, problems with air propagation are minor, because of the short measurement distance. However, the near field is characterized by a high reactive sound power, due to a phase shift of sound pressure and velocity. Therefore, the simple extrapolation to the far field using the 1/r law (-6dB for doubling the distance) is not valid.

Holographic Approach

The spherical wave expansion provides a model, which can characterize the near field effects by solving the wave equation. According to [1], the complex sound pressure p at a complete surface is described by a multi sum of orthonormal basic function and complex weighting coefficients $C_{n,m}$.

$$p(r,\phi,\theta,\omega) = \sum_{n=0}^{N} \sum_{m=-n}^{n} C_{n,m}(\omega) \cdot h_n^{(2)}(kr) \cdot Y_n^m(\phi,\theta) \quad (1)$$

The set of basis functions is the product of Hankel functions of the second kind $h_n^{(2)}$ and spherical harmonics Y_n^m. The spherical harmonics characterizes the angular dependency over the spherical angles phi and theta. As shown in figure 1 spherical harmonics correspond to elementary sources.

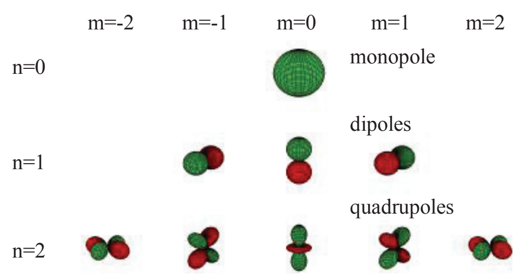

Figure 1: First orders of spherical harmonics (real parts)

The Hankel functions are a special solution of the wave equation. They characterize the radial propagation of the sound wave from near into far field. With the phase definition of a negative phase shift over distance, the Hankel function of the second kind represents an outgoing wave.

The sound field of a loudspeaker has a limited complexity. Thus, it can be characterized by limited number of expansion term. Furthermore, in contrast to conventional far field measurement the accuracy of the results is not dependent from the number of measurement points, but from the complexity of the sound field. That means, a simple sound source e.g. a subwoofer can be completely characterized by multipole up to order N=5 (36 coefficients).

After identifying the coefficients at the measurement surface, the radiated sound field of the device can be extrapolated into free field to any point in 3D space outside the scanning surface. That means the set of coefficients totally represents the sound field in both near and far field.

Measurement Setup

The spherical wave expansion requires multiple measurements on a complete three-dimensional surface. Therefore, the data acquisition is performed by an automatic measurement system, the Klippel Near Field Scanner. The robot is a microphone positioning system, based on cylindrical coordinates. During a measurement, the microphone is positioned at multiple points on a cylindrical surface around the device. At each measurement point, the transfer function is measured. The device under test (DUT) is placed in the center of the Near Field Scanner and is not moved during the measurement. Thus, the scanner can measure very heavy loudspeaker up to a weight of 500kg, hanging on a ceiling crane. In addition, the non-moving loudspeaker ensures a constant room response, which allows field separation techniques and the measurement in a normal office room.

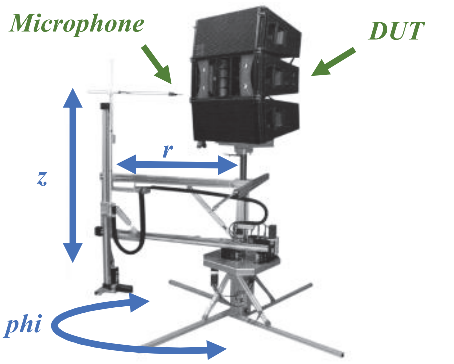

Figure 2: Klippel Near Field Scanner 3D

Results

An important measure, which is a direct indicator for the accuracy of the spherical wave expansion, is the Fitting Error. It is defined as a relative mean square error between the measured sound pressure p_{meas} and modeled sound pressure p_{mod} over all measurement points M.

$$e_{fit} = \frac{\sum_{i=1}^{M} \left| p_{i,\mathrm{mod}} - p_{i,\mathrm{meas}} \right|^2}{\sum_{i=1}^{M} \left| p_{i,\mathrm{meas}} \right|^2} \cdot 100\% \qquad (2)$$

The fitting error is visualized as power error in dB, so -20dB is comparable to 1% error. The following example shows the fitting error from the measurement of a studio monitor for different orders N.

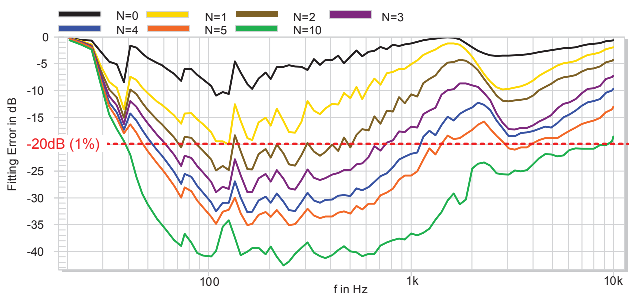

Figure 3: Fitting Error over frequency for orders N=0 to N=10 from the measurement of a studio monitor

As seen in the picture, the monopole (N=0) is insufficient to characterize the sound field. Increasing the order, the fitting becomes more accurate. For an order of N=10 the model completely describes the measured sound field. Only for very low frequencies (f<50Hz), the fitting error is still above the threshold of -20dB. In this frequency range, the speaker is out of its working range, so the error is caused by noise. Extrapolating the identified sound pressure into far field the results can be directly compared with a traditional far field measurement. The following example shows the comparison of a near field scan, measured in reverberant room at the TU-Dresden and far field measurement measured at the anechoic room of the RWTH Aachen. The measurement object is a professional audio line array.

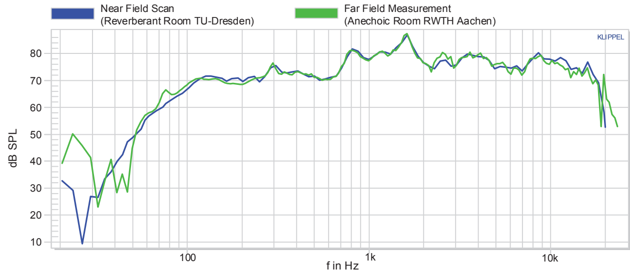

Figure 4: On-Axis response comparison of near field measurement (reverberant room TU-Dresden) and far field measurement (anechoic room RWTH Aachen)

As seen in the picture, the anechoic room has an insufficient damping below 100Hz. In contrast, the near field measurement provides better results below 100Hz. Because of the field separation, the room reflection were identified and separated from the radiated sound pressure. For very high frequencies, there is a small mismatch between the two measurements. This is caused by a small On-Axis angle mismatch between the two measurements.

Summary

Spherical wave expansion is a powerful alternative for the measurement of 3D directivity. It provides a comprehensive data set, which has low redundancy and gives more information than a conventional far field measurement. Because of exact modelling of the sound radiation from near into far field, the sound pressure at any point in 3D space outside the scanning surface can be extrapolated. The method requires less measurement points (<1/10 of far field) and less measurement time. It combines the benefits of near field measurements like high SNR, high direct sound and no problems with air propagation with the ability to measure the far field directivity. Room reflection and resonances can be separated, allowing full band measurement in a normal office room.

References

[1] E. G. Williams. Fourier Acoustics – Sound Radiation and Nearfield Acoustical Holography.
Academic Press 1999

[2] G. Weinreich, E. B. Arnold. Method for measuring acoustic radiation fields.
J. Acoust. Soc. Am., 68 (2), 404–411, 1980

[3] M. Melon, C. Langrenne, A. Garcia. Measurement of subwoofers with the field separation method: comparison of p- p and p-v formulations.
Proc. Acoustics 2012 Nantes, 3491-3496, 2012

[4] Z. Wang, S. F. Wu. Helmholtz equation-least-squares method for reconstructing the acoustic pressure field.
J. Acoust. Soc. Am., 102 (4), 2020-2032, 1997