Holographic Measurement of the 3D Sound Field using Near-Field Scanning

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AGENDA

1. Pros and Cons of Conventional Loudspeaker Measurements
2. New Requirements for Comprehensive 3D Directivity Data
3. Introduction to Directivity Measurements
4. Near Field Measurements can be Beneficial!
5. A New and Better Way using Near Field Scanning
6. What is Spherical Harmonic Wave Expansion?
7. Coefficients, Spatial Resolution, Number of Measurement Points and the Order of the Expansion
8. Practical Applications and Test Cases
9. Conclusions
Conventional Loudspeaker Measurements

- **Far-Field Measurements in Anechoic Chambers** (1930’s, Beranek and Sleeper 1946)
  - Absorption of room reflections above cutoff frequency (depends on chamber dimensions)
  - High ambient noise isolation
  - Controlled climate conditions

- **Far-Field Measurement under simulated Free-Field Conditions**
  by gating or windowing the impulse response (Heyser 1967-69, Berman and Fincham 1973)
  - Suppression of room reflections at higher frequencies (depends on room dimensions)
  - Higher SNR due to ambient noise separation
  - Limited low frequency resolution (depends on time difference between direct sound and first reflection)
Problems

- Low frequency accuracy and resolution limited by acoustical environment (room dimensions and treatment)
- Far-Field measurement conditions required
- Accuracy of the phase response in the far-field depends on air temperature deviations and movement
- An anechoic chamber is not perfect. (dimensions, irregular absorption)
- An anechoic room is an expensive long-term investment which cannot be moved easily
Problem #1…The Acoustical Environment

→ room dimensions are the limiting factor for low frequency measurement accuracy and resolution!
Problem #2…Why are Far-Field Conditions Required?

What is heard and measured in the near field is difficult to predict and not a reliable indicator of events in the far field.

In the far field, the source is small compared to the measurement distance and the sound level falls at 6 dB per doubling the distance. (1/r law).

→ Sound pressure measured in the near-field cannot be extrapolated into the far-field!

Problem #3...Phase response accuracy

Sound velocity is dependent on air temperature:

A temperature difference of $\Delta \vartheta = 2^\circ C$ will change the sound velocity by $\Delta c \approx 1.2\, \text{m/s}$

The temperature difference will influence the sound wave propagation time:

\begin{align*}
\vartheta_1 &= 20^\circ C \rightarrow c_1 = 343.4\, \text{m/s} \\
\vartheta_2 &= 22^\circ C \rightarrow c_2 = 344.6\, \text{m/s} \\
\vartheta_3 &= 24^\circ C \rightarrow c_3 = 345.8\, \text{m/s}
\end{align*}

Deviation:

$\Delta t = 0.1\, \text{ms}$  
($\Delta r = 34.3\, \text{mm}$)

Phase errors caused by temperature difference of $2^\circ C$:

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Wave length (mm)</th>
<th>Phase Error in 5 m distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f=2$</td>
<td>$\lambda = 171.7$</td>
<td>$36^\circ (0.1, \lambda)$</td>
</tr>
<tr>
<td>$f=5$</td>
<td>$\lambda = 68.7$</td>
<td>$90^\circ (0.25, \lambda)$</td>
</tr>
<tr>
<td>$f=10$</td>
<td>$\lambda = 34.3$</td>
<td>$180^\circ (\lambda)$</td>
</tr>
</tbody>
</table>

Far field measurement are prone to phase errors!
Problem #4…No anechoic room is perfect!

How to cope with limited absorption at low frequencies?

1. Select reference loudspeaker sample
2. Measure in the far-field in the anechoic room
3. Measure again under free-field conditions
4. Calculate a room correction curve and apply to get a simulated free field response.

Note: Room correction curve depends on loudspeaker properties!!

insufficiently damped for frequencies below 100Hz
New Requirements for Comprehensive 3D-Directivity Data

- **Home Audio**
  To predict how a loudspeaker might sound in a typical listening room, CEA2034-2013 specifies a 360 degree polar measurement largely based on the techniques developed by Toole and Devantier at Harman (a.k.a the spinorama test)

- **Handheld Personal Audio Devices**
  The near-field response generated by laptops, tablets, smart phones, etc. is more important than the far field response (considered in new proposal IEC60268-2014)

- **Studio Monitor Loudspeakers**
  Professional reference loudspeakers need a careful evaluation in the near-field

- **Professional Stage and PA Equipment**
  Accurate complex directivity data in the far-field is required for room simulations and sound system installations (line arrays)

How do we use current measurement techniques to satisfy these new requirements?
How to Perform Directivity Measurements in the Far Field?

The sound pressure is measured at multiple measurement points located on the surface of a sphere with radius r. The DUT is rotated.

The # of pts. depends on desired resolution:

- 5 degree → 2592 points
- 2 degree → 16200 points
- 1 degree → 64800 points

Accuracy depends on:
- tolerance of mic placement (both θ and r) (phase!)
- Maintaining the acoustic center when changing the DUT position
- Sound reflections from turntable
- Room absorption irregularities
- Temperature deviations and air movement (phase!)

→ When reducing the number of measurement points, weighted spatial averaging is an estimation!
Near Field Measurements can be Beneficial!

Advantages:
- High SNR (typically 20 dB more than far-field measurements)
- Amplitude of direct sound much greater than room reflections providing good conditions for simulated free field conditions
- Minimal influence from air properties (air convection, temperature deviations)
- Faster measurements since no averaging required
- Measurements can tolerate some ambient noise (office, workshop)

Disadvantages:
- Not a plane wave
- Velocity and sound pressure are out of phase
- Inverse square law \( (1/r) \) does not apply, therefore, no sound pressure extrapolation into the far-field

The limiting factor for useful near field measurements is the inverse square law \( (1/r) \)
Some Recent Contributions... Scanning the Sound Field on a Surface Around the Source

- Weinreich (1980)
- Melon, Langrenne, Garcia (2009)
- Bi (2012)
A New and Better Way…

Exploiting the Advantages of Near-Field Measurements and Overcoming the Disadvantages using Spherical Harmonic Wave Expansion

- Near-field sound pressure can be extrapolated into the far-field
- Room dimensions are no longer a factor
- No anechoic environment required
- Far-field conditions are no longer necessary
- High spatial resolution can be obtained using less measurement points
- Comprehensive data set…one measurement does all…the 3D acoustic output is the result of post-processing
- Faster 3D directivity measurements
The General Approach

Step 1...Scanning process: measurement of the near field sound pressure distribution using robotics

Step 2...Spherical Harmonic Wave Expansion: post-processing of the measured near-field data including sound field separation techniques

Step 3...Extrapolation: calculation of the sound pressure at any point outside the scanning surface (near-field and far-field)
Step 1...The Scanning Process in the Near-Field

Moving the DUT or the Mic in the Near-Field?

Moving the microphone has the following advantages:

- Accurate positioning of Mic
- Facilitates heavy loudspeakers (hanging from a crane)
- Constant DUT interaction in the room during the scan (required in a non-anechoic environment)
- Minimum gear within the scanning surface (only a platform and a pole)
Scanning Multiple Layers to Facilitate Field Separation

A double layer scan provides information about the incoming and outgoing sound waves which can be used to separate the directly radiated sound from the room reflections.

Note: Under anechoic conditions, the high SNR in the near field combined with wave expansion techniques eliminates the need for field separation.

We need to use Field Separation in a non-anechoic environment.
General solutions of the wave equation are used as basic functions in the expansion. The weighted coefficients determine the contribution from each function. Total number of coefficients $= (N+1)^2$
How to Interpret the Coefficients?

\[ H(f, r) = C(f) B(f, r) \]

- The coefficients in vector \( C(f) \) are complex and frequency dependent. They weight each basic function in the solution of the wave equation.
- The number of coefficients depends on frequency (and complexity).

\[
\begin{align*}
\text{number of coefficients} &= (N+1)^2 \\
9 &\quad 36 &\quad 121 \\
\text{order of the expansion} &\quad N > 2 &\quad N > 5 &\quad N > 10 \\
\text{frequency} &\quad 100 \text{ Hz} &\quad 1 \text{ kHz} &\quad 10 \text{ kHz}
\end{align*}
\]

- Significant data reduction occurs when the measurement points are converted into coefficients.
- Truncating of the order has the effect of smoothing the directional properties (lobes).
- Wave expansion interpolates between the measurement points.
How Many Points Need to be Measured?

Number of points required depends on:

- Loudspeaker type (size, number of transducers) (i.e. complexity of the sound field)
- Symmetry of the loudspeaker (axial symmetry)
- Application demands (e.g. High resolution EASE data)
- Field separation (required for improved accuracy at low frequencies under non-anechoic conditions)

In general, the number of points is 1.5 times the number of coefficients.

Note: Number of measurements points required is much lower than the final angular resolution of the calculated directivity pattern!
High Angular Resolution Only Requires a Few Measurement Points

Example: **Woofer**

At low frequencies, the sound field has a limited complexity and can be characterized by a small number of basic functions.

**Directivity patterns at 200 Hz:**

- Target
- N=0
- N=1
- N=2
- N=3
- N=10

*sound field is completely described by order N=3 (16 Coefficients)*
How to Check the Accuracy of the Wave Field Expansion?

- Number of measurement points is larger than the number of coefficients (16) which leads to a fitting problem (redundancy of information)
- This redundancy is used to calculate the fitting error in dB
- The fitting error indicates potential problems (poor SNR, insufficient order, geometrical errors in the scanning)
How to Find the Maximum Order N?

The measurement system determines automatically:
- optimum order N of the wave expansion
- total number of the measurement points
- measurement time

Fitting error as a function of the maximum order N

Directivity at 2kHz:

Target

N=0

N=1

N=2

N=5

N=10

Sufficient accuracy
Test Case #1…SPL Comparison
Anechoic Environment vs. Reverberant Room
Using Line Array

Far-field in the anechoic room
(half space at RWTH Aachen)
• Half space \((2\pi)\) measurement
  (microphone on ground)
• DUT rotated by robotics arm
• 4050 points measured on a quarter sphere at 7m (symmetry assumed to avoid measuring 16200 points)

Near-field scanning in the reverberant room
(at the TU Dresden)
• DUT placed at fixed position
• Microphone moved by near field scanner
• 4000 points full scan (no symmetry assumed)
• Maximum order \(N=30\)
Performance of the Field Separation Technique at Low Frequencies

Benefits of Field Separation:
- No anechoic conditions required
- No (long) time windowing
- High resolution
- Low order N of expansion
- Minimal number of measurement points (<20)

Measurement in a Reverberant Room on axis one point
Better Accuracy using Near-Field Scanning?

Near field scanning + field separation can remove the room modes in a reverberant environment!
More Angular Resolution with Less Points

Far-Field Measurement
in anechoic room
(assumed symmetry)
16200 pts

Full Near-Field Scan in
Reverberent Room
4000 pts

WAVE EXPANSION interpolates between the measurement points!
Test Case #2...Directivity and Sound Power using a Studio Monitor

- Near-field scanning in an ordinary office room
- 500 points
- Order of expansion N=20
What is the Accuracy of a Sound Power Measurement (20 min scan time)

Fitting error from the post-processing shows the accuracy of the results!!

Radiated Sound Power

2500 Points (8 hrs)
100 Points (20 min.)

Deviation: < 0.5 dB < 1 dB

Fitting Error vs. Frequency

noise

1 % Error

2500 Points
100 Points
Satisfies Requirements of CEA-2034

Fast (single point) SPL Measurements in the Near-Field are Possible using a Correction Curve

Assumption:
• Loudspeakers of the same type with similar geometry have similar directivities

PROBLEMS:
• 1 point is insufficient for correct processing
• No field separation
• No far field extrapolation

• complete scan in the near field of a reference DUT
Determing the location of the near and far-fields is important for personal and handheld audio devices!!
Comprehensive 3D Information supports the evaluation of spatial sound effects.
Near-field Information

is important for 3D sound effects

Sound pressure distribution (3kHz)

Comprehensive Information

Wave front propagation (3kHz)

Observation plane

r = 0.5m (near field)

r = 2m (far field)

Variation versus distance

(r = 0.5m)

Wave front propagation (3kHz)
Holographic Measurement of the 3D Sound Field using Near-Field Scanning provides the following benefits:

- More information about the acoustical output (near-field + far-field)
- Sound pressure at any point outside scanning surface (complete 3D space)
- Improved accuracy compared to conventional far-field measurements (coping with room problems, gear reflections, positioning, air temperature, ...)
- Higher angular resolution with less measurement points
- Simplified handling (moving of heavy loudspeakers)
- Dispenses with an anechoic room
- Self-check by evaluating the fitting error
- Comprehensive data set with low redundancy
Thank you!