#### 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?



"Toole, F. (2008). Sound Reproduction: The Acoustics and Psychoacoustics of Loudspeakers and Rooms"

→ 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  $\Delta c \approx 1.2$  m/s

$$\begin{split} \mathcal{G}_1 &= 20^\circ C \rightarrow c_1 = 343.4 \, m/s \\ \mathcal{G}_2 &= 22^\circ C \rightarrow c_2 = 344.6 \, m/s \\ \mathcal{G}_3 &= 24^\circ C \rightarrow c_3 = 345.8 \, m/s \end{split}$$

The temperature difference will influence the sound wave propagation time:



Phase errors caused by temperature difference of 2°C:

Frequency	Wave length	Phase Error in 5 m d	istance
<i>f</i> =2kHz	λ=171.7mm	36° (0.1 λ)	
<i>f</i> =5kHz	λ=68.7mm	90° (0.25 λ)	Far field measurement are
<i>f</i> =10kHz	λ=34.3mm	180° (λ)	prone to phase errors !





## Problem #4...No anechoic room is perfect !

How to cope with limited absorption at low frequencies ?

#### Anechoic room



insufficiently damped for frequencies below 100Hz





Simulated Free field response





Note: Room correction curve depends on loudspeaker properties !!





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





## 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 Not practical

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:** postprocessing of the measured near-field data including sound field separation techniques

**Step 3...Extraplation:** 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







### Step 2...Spherical Harmonic Wave Expansion



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 ?



- 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)

nber of coefficients = $(N+1)^2$	9	36	121
order of the expansion	N > 2	N > 5	N > 10
frequency	100 Hz	1 kHz	10 kHz

- 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



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## 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 seperation (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





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:

- $\rightarrow$  optimum order N of the wave expansion
- $\rightarrow$  total number of the measurement points
- $\rightarrow$  measurement time

Fitting error as a function of the maximum order N



Directivity at 2kHz:



KLIPPEL, WARKWYN: Near field scanning, 33

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



Elf System made by Four Audio Aachen



#### Far-field in the anechoic room (half space at RWTH Aachen)

Half space (2π) 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 measurment points (<20)</li>







#### Better Accuracy using Near-Field Scanning?







## More Angular Resolution with Less Points



#### 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 postprocessing shows the accuracy of the results !!



KLIPPEL, WARKWYN: Near field scanning, 41



## Satisfies Requirements of CEA-2034



"Toole, F. (2008). Sound Reproduction: The Acoustics and Psychoacoustics of Loudspeakers and Rooms"





## 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



#### Test Case #3...Comprehensive 3D Information using a Laptop Is the User Located in the Near-Field or Far-Field?



Determining 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







### A New and Better Way Summary

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 measruements (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 !



