**Fundamentals**

**Spherical Wave Expansion**

The complex transfer function \( W(f) \) relating loudspeaker input \( V \) to sound pressure \( p \) at a particular point \( x \) is approximated by the convolution of spherical harmonics \( Y_{nm} \) with the spherical radiator \( r \):

\[
W(f) = \sum_{n=0}^{N} \sum_{m=-n}^{n} \left( \frac{2n+1}{4\pi} \right)^{1/2} \hat{Y}_{nm}(f) Y_{nm}(x/r)
\]

Where \( \hat{Y}_{nm}(f) \) are the spherical harmonics of order \( n \) and degree \( m \). The expansion is truncated at a maximum order \( N \) that is limited by the resolution of the measurement technique.

**Orthogonal Decomposition**

The decomposition into orthogonal basis functions \( \{r^{m}(\theta, \phi)\} \) provides a comprehensive representation of the 3D sound radiation:

\[
W(f) = \sum_{m=0}^{N} \hat{r}^{m}(f) r^{m}(\theta, \phi)
\]

The maximum required order \( N \) depends on the complexity of the directivity pattern generated by the loudspeaker.

**Higher-order terms**

- \( n=0 \): constant value \( \hat{r}^{0}(f) \)
- \( n=1 \): linear component \( \hat{r}^{1}(f) \)
- \( n=2 \): quadratic component \( \hat{r}^{2}(f) \)

Higher-order terms are required to model the directivity at higher frequencies in order to achieve sufficient angular resolution and accuracy.

**Sound Separation**

Measurements of the sound pressure generated by a loudspeaker in a non-anechoic environment show interference between the direct sound component and the reflections produced by the room. At higher frequencies, the direct sound can be isolated by subtracting the impulse response. At low frequencies, the subtracting interference requires a large distance between the speaker and the reflecting boundaries in order to provide sufficient spectral resolution.

**Sound Field Extrapolation**

In the far field, the sound pressure is directly proportional to the distance \( r \) and can be calculated using the inverse square law:

\[
p(r) = p_{0}(f) \frac{1}{r^2}
\]

Where \( p_{0}(f) \) is the sound pressure at any frequency \( f \) and \( r \) is the distance from the source to the point of measurement.

\( r \) is the distance from the focal point of the near field.

Near Field Characteristics

The far-field characteristics offer a simple and intuitive representation of the directivity at high frequencies. The far-field directivity is the same as the near-field directivity, but with different scaling.

**Far Field Characteristics**

- **Frequency Response**
- **Sound Power**
- **Directivity Index**

- **3D Directivity**
  - Contour Plot
  - Polar Plot
  - Directivity Ballistics
  - Coverage Angle

**Near Field Characteristics**

Near field characteristics are especially relevant for studio monitors, smartphones, laptops, and other personal audio devices. An anechoic test environment can provide an intuitive representation of the directivity at low frequencies.

**Holographic Processing**

Holographic processing produces a directivity pattern that is obtained by measuring the sound pressure at multiple points in the near field and calculating the directivity at each point.

**Simplified Interpretation**

Testing personal audio devices, the IEC 60268 standard specifies the measurement characteristics in personal acoustic zones in the near field of the sound source.

**Single Point SPL Measurement**

- **Input Power**
- **Output SPL**
- **Directivity Index**

- **3D Sound Separation**
  - Near Field
  - Far Field
  - 3D Directivity

Distributed Sound Sources

The distribution of distributed sound sources (arrays, sound bars) can be determined by analyzing the sound pressure at multiple points in the far field.

**Applications**

**Holographic Loudspeaker Testing**

ASSESSING RADIATED SOUND IN 3D SPACE

- **Near Field Scanning**
- **Far Field Characteristics**

**References**


**Measurements**

- **Parameter Identification**
- **Near Field Scanning**
- **Far Field Characteristics**

**Assessment**

- **Near Field Scanning**: 3D Directivity
- **Far Field Characteristics**: Frequency Response, Sound Power, Directivity Index

**Near Field Scanning**

The soundfield is measured using two cylindrical or hemispherical surfaces in the device’s near field. While still yielding the same angular resolution of the directivity pattern, the holographic approach requires a lower number of measurement points than traditional techniques.

**Far Field Characteristics**

The frequency response of the loudspeaker at any point in the far field can be reproduced from near-field data.

**Near Field Scanning**

- **Frequency Response**
- **Sound Power**
- **Directivity Index**

- **3D Directivity**
  - Contour Plot
  - Polar Plot
  - Directivity Ballistics
  - Coverage Angle

**Near Field Characteristics**

- **Frequency Response**
- **Sound Power**
- **Directivity Index**

- **3D Directivity**
  - Contour Plot
  - Polar Plot
  - Directivity Ballistics
  - Coverage Angle

**Distributed Sound Sources**

The directivity of distributed sound sources (arrays, sound bars) can be determined by measuring each individual transducer of the loudspeaker system. The measurement characteristics of each transducer also includes shadowing and diffraction effects of the loudspeaker cabinet. After holographic processing, the total radiated sound pressure is calculated by superimposing the individual sound sources. By applying separate filters on each transducer (e.g., delay, gain), the directivity of the active system can be easily controlled (beaming control).