Sound field decomposition of sound sources used in sound power measurements

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Summary

For the establishment of traceability in sound power measurements, two major types of sound sources are proposed to be used. The first is a primary source which is a baffled vibrating body. The second source type is called transfer source and it generates sound aerodynamically. It is planned to calibrate transfer sources by comparison with the primary source by applying an enveloping surface method using sound pressure. Therefore, the sound field created by a primary source and three transfer sources was measured in terms of sound pressure over a fully enveloping hemisphere. The measured sound pressure values formed the basis for the sound field decomposition by implementing a spherical harmonics transform. This enabled the detailed visualization of the sound pressure distribution over each source. The emission characteristics described by the spherical harmonics order were compared to the corresponding characteristics determined from measurements at various ambient temperatures and the results are presented.

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1. Introduction

The establishment of traceability in sound power [1] requires two groups of sources. The first group contains the primary standards, where the unit watt is realised by determination of non-acoustic quantitities. The other group contains the transfer (secondary) standards, to enable the dissemination procedure [2] from calibration (laboratory) conditions to in-situ conditions. The comparison between the known sound power of a primary source and the unknown sound power of a source under test is intended to be performed using the substitution method [3], which requires the measurement of the sound pressure level produced by each source. For the analysis and comparison of the radiation pattern characteristics, which are important to sound power determination, the spherical harmonics transform was used.

2. Sound pressure measurements

The substitution method is used for the determination of an unknown sound power level of a source in comparison to the known sound power level of another source following the expression [3]:

$$L_{W,2} = L_{W,1} + \overline{L_{p,2}} - \overline{L_{p,1}} \qquad (1)$$

where $L_{W,2}$ is the unknown sound power and $L_{W,1}$ the known sound power level. $\overline{L_{p,1}}$ and $\overline{L_{p,2}}$ is the time and surface averaged sound pressure level of the known and the unknown source respectively.

Figure 1. The primary source (left) and the reference sound sources used in this study.

For the present study, PTB's primary standard was used [4], which is a vibrating piston embedded in the floor of PTB's hemianechoic room. As transfer standards, three types of aerodynamic reference sound sources (RSS) were chosen. All sources are depicted in Figure 1.

The sound pressure measurements were performed in PTB's hemianechoic room using the specially designed PTB's scanning apparatus, which is shown in Figure 2. The scanning apparatus consists of a hemispherical arc (two arcs are available for different measurement radii as shown in figure 2), where up to 24 free-field condenser microphones can be positioned and an external motor, which enables the arc to cover a hemisphere. A more detailed study on the scanning apparatus may be found in [5].

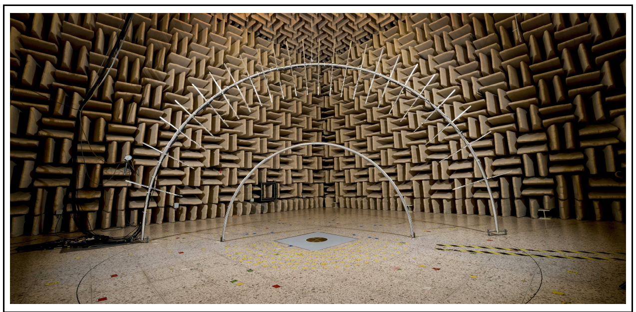

Figure 2. PTB's scanning apparatus.

3. Spherical harmonics transform

Similarly to the Fourier transform, by which the frequency content of a time signal is described by a sum of sine waves, the spherical harmonics transform (SHT) is used for the analysis of a radiation pattern. The basis for the SHT are spherical harmonic functions, which enable the decomposition of the sound field into a sum of spherical harmonics.
Consider a sound field, where the sound pressure values on a spherical surface, which surrounds a source, are expressed using a spherical coordinates system (r = radius, θ = elevation angle, φ = azimuthal angle) in the form of $p(k,r,\theta,\varphi)$, with k being the wavenumber. If the sound field is square-integrable on the surface of the sphere, the sound pressure values can be expressed as a spherical harmonics series according to [6]:

$$p(k,r,\theta,\varphi) = \sum_{n=0}^{N} \sum_{m=-n}^{n} p_{nm}(k,r)\, Y_n^m(\theta,\varphi) \tag{2}$$

The basis functions $Y_n^m(\cdot,\cdot)$, which are commonly refered as the spherical harmonics of order n and degree m, are given by:

$$Y_n^m(\theta,\varphi) \triangleq \sqrt{\frac{2n+1}{4\pi}\frac{(n-m)!}{(n+m)!}}\, P_n^m(\cos\theta) e^{im\varphi} \tag{3}$$

where $P_n^m(\cdot)$ is the associated Legendre function of order n and degree m.
Figure 3 shows the first two orders of the real part of the spherical harmonic functions. The magnitude of the functions is represented by the radius and the phase by the colour.

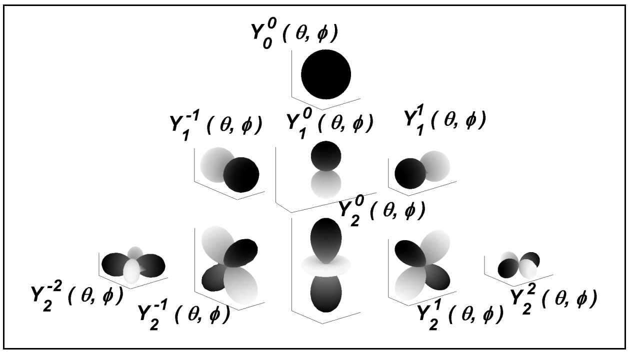

Figure 3. First two orders of the real part of the spherical harmonics functions.

The pressure coefficients p_{nm} of equation 2 can be calculated by the spherical harmonics transform of the spatial pressure function according to:

$$p_{nm}(k,r) = \int_{\theta=0}^{\pi} \int_{\varphi=0}^{2\pi} p(k,r,\theta,\varphi)\, Y_n^{m*}(\theta,\varphi) \sin\theta \, d\theta d\varphi \tag{4}$$

where $Y_n^{m*}(\cdot,\cdot)$ is the spherical harmonics functions complex conjugate.
If the sound pressure coefficients are known through equation 4, it is possible to calculate the sound pressure at any point outside the sphere, which contains all sources [7].

4. Measurement data analysis

The sound pressure measurements were performed for three different radii (1.45, 1.70 & 2 m) and each scan had 1200 s duration. Three measurements for each radius were performed, resulting to 12 spatial data sets for each source. Post analysis of the time recorded signals divided each microphone trajectory to 171 segments. For each segment, the averaged sound pressure was calculated, providing a hemispherical grid of 4104 points.

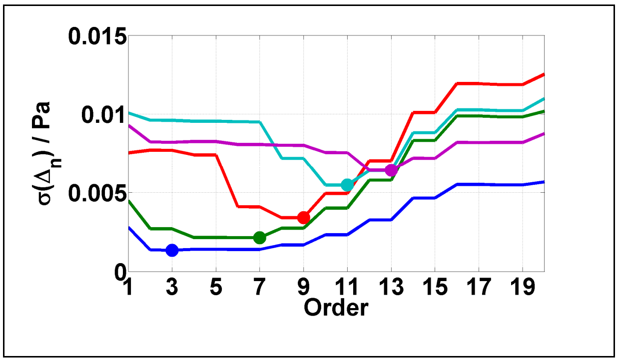

Figure 4. Determination of spherical harmonics order for five different 1/3 octave bands (different colours) for a reference sound source. The dots represent the selected order for each band.

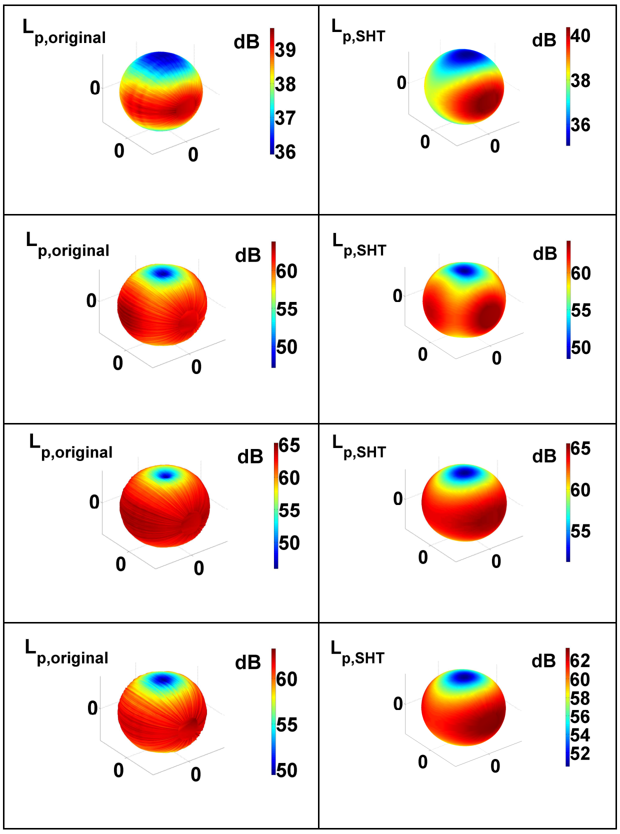

Figure 5. Sound pressure level over a sphere for the primary source (first row) and three reference sound sources (other rows) at 80 Hz. Left column: originally measured data. Right column: Data after spherical harmonics transform.

The previously described spherical harmonics analysis refers to sound pressure measurement over a sphere. For this reason, the hemispherical measurement grid was used for the creation of a spherical one, by assuming symmetry over the highly reflecting hemianechoic room floor.

The originally measured sound pressure data was used for the determination of the spherical harmonics order. This was experimentally performed, as follows: each measured sound pressure set (p_{meas}) was used for the calculation of the sound pressure coefficients p_{nm} using equation 4 for all orders up to a maximum ($n_{\max}$= 20). The sound pressure coefficients were then used for the calculation of new sound pressure values (p_{SHT}) according to equation 2. The difference between the original sound pressure data and the sound pressure values after the spherical harmonics transform was then calculated for each order:

$$\Delta_n = p_{\text{SHT},n} - p_{\text{meas},n} \tag{5}$$

Equation 5 provided as many differences as measurement grid points. The standard deviation of all differences for each measurement set was calculated per frequency and the order that corresponded to the minimum standard deviation, was selected for further calculations. Equation 6 summarizes the spherical harmonics order calculation:

$$n(f) = min\{\sigma[\Delta_n(f)]\} \tag{6}$$

The aforementioned analysis was performed using the ITA-Toolbox [8].
Figure 4 shows an example of the determination of the spherical harmonics order for five 1/3 octave bands according to equation 6.

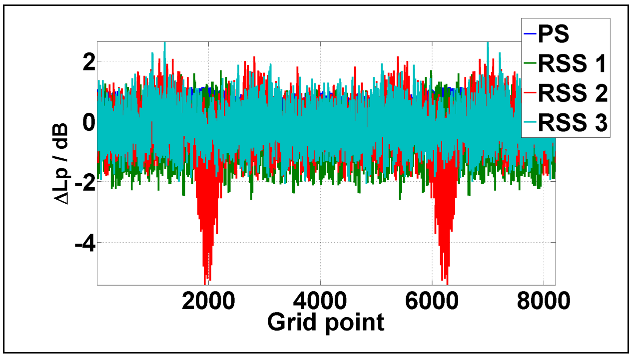

Figure 6. Sound pressure level difference between the originally measured sound pressure and the sound pressure using the spherical harmonics transform coefficients for each measurement grid point.

Figure 5 shows the sound pressure distribution over a sphere for both the measured and the spherical harmonics transform data for the 1/3 octave band of 80 Hz. It can be seen that the spherical harmonics transform provided data close to the measured.

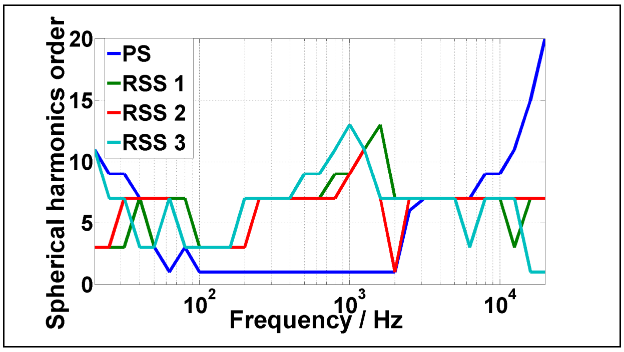

Figure 7. The spherical harmonics order for all sources under test against frequency.

Figure 6 shows an example of the sound pressure level difference between the originally measured sound pressure levels and the levels using the spherical harmonics transform coefficients for the data of Figure 5. The differences between the surface averaged sound pressure levels are 0.08, 0.17, 0.15 & 0.15 dB respectively. These values validate the experimental approach for the determination of the spherical harmonics order.
Figure 7 shows the spherical harmonics order used for each source. The increase in the order of the primary source towards higher frequencies is attributed to the influence of background noise.
Another important aspect of the spherical harmonics transform is the energy distribution to each harmonic, which was also calculated using the ITA-Toolbox [8]. Figure 8 shows the energy distribution to each spherical harmonic of the transformed signals of Figure 5. As it can be seen in Figure 8, the energy distribution depends on frequency and on type of source.
The differences in the radiation characteristics as seen in Figures 7 & 8 are of great importance, since they may affect the substitution method. Theoretically, the substitution between two sources of different radiation order (e.g. a monopole substituted by a dipole) may be performed. To relate any theoretical findings to measurement results would require the unique characterization of each measured source based on its energy distribution.
For this reason, the expected value of the order was calculated for each source using:

$$n_{\mathrm{expected}} = \sum_{n=0}^{n_{\max}} \frac{nE_n}{E_{\mathrm{tot}}} \qquad (7)$$

where n is the spherical harmonics order, E_n the energy of each spherical harmonic and E_{tot} the total energy of the signal.

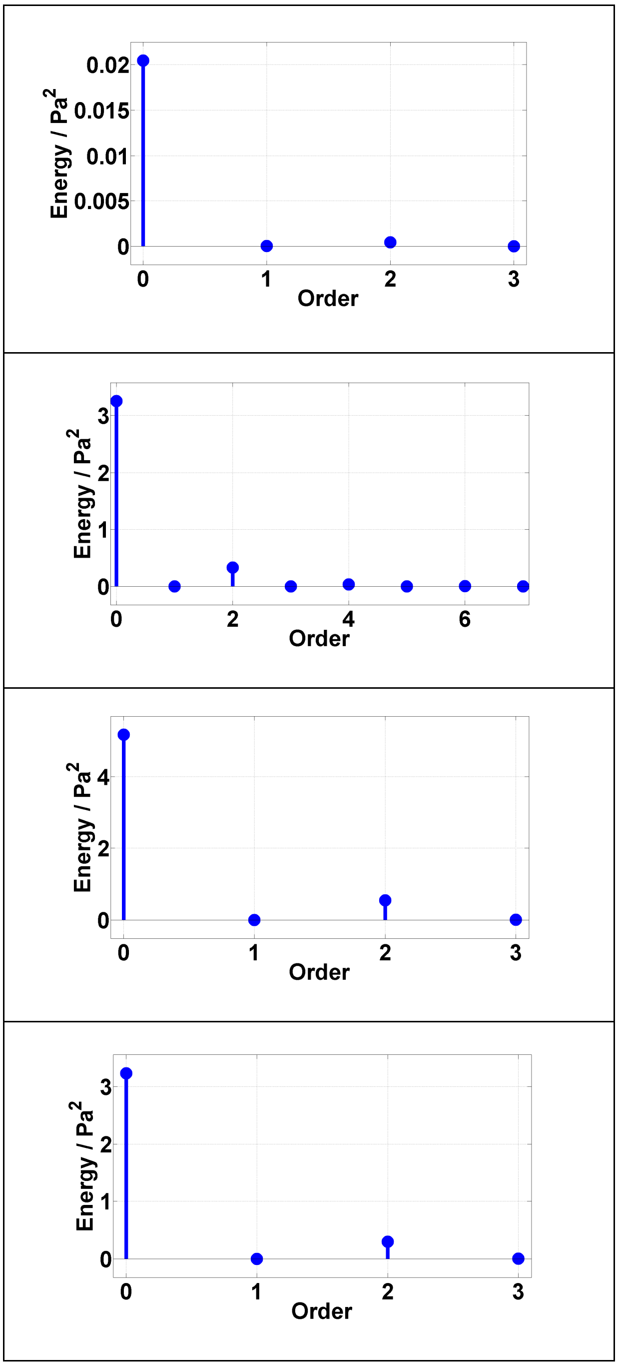

Figure 8. Spherical harmonic energy distribution for the corresponding signals of the right column in Figure 5.

Figure 9 shows the expected value for all sources under test. The calculation of the expected value was performed for all measurement data and the mean value was then derived. It is interesting to notice that the primary source is well described by a source of order 0 between 40 Hz and 2 kHz. The order is only slightly larger for the aerodynamic reference sound sources.

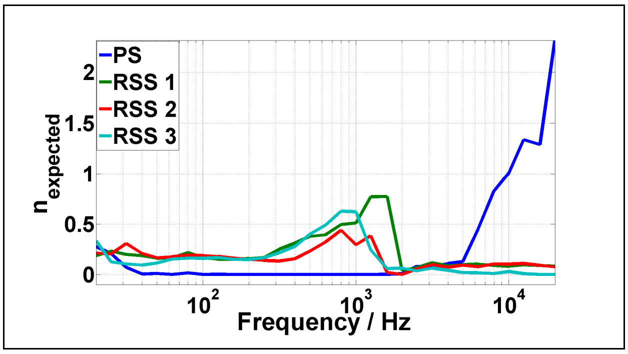

Figure 9. Expected value of spherical harmonics order for all sources under test against frequency.

The sound power generated by an aerodynamic source is related to the atmospheric pressure B, the ambient temperature T and the rotation speed ω via [9]:

$$P = K\,B\,T^{q}\omega^{5.5} \qquad (8)$$

where K is a constant and q is related to the source radiation order (-1 for monopole, -3 for dipole etc.). To account for the effects of changes in temperature during the determination of sound power a study was performed and a correction factor was estimated [10]. The correction factor exT is related to the source radiation order q according to:

$$exT = \frac{(q-2)}{2} \qquad (9)$$

q is related to the spherical harmonics order through:

$$q = -(2n+1) \qquad (10)$$

Using equations 9 and 10, the experimental correction factor values may be related to the spherical harmonics order as:

$$n = -exT - 3/2 \qquad (11)$$

Figure 10 shows the spherical harmonics order of the aerodynamic reference sound sources according to the measurements and the spherical harmonics transform along with the theoretically expected value.

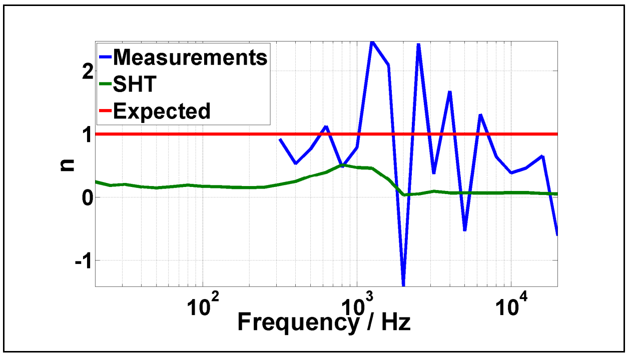

Figure 10. RSS spherical harmonics order after measurements, spherical harmonics transform and expected value against frequency.

5. Conclusions

The substitution method is intended to be used for the establishment of traceability in sound power measurements. The radiation characteristics of the sources used is therefore of great importance. The decomposition of the sound field produced by a vibrating piston (primary source) and three aerodynamic reference sound sources (transfer sources) was performed in terms of spherical harmonics.

The sound field decomposition of the primary source revealed a monopole behaviour for the frequency range from 40 Hz to 2000 Hz, which was theoretically expected due to the related sound generating mechanism.

The analysis of the sound field of the transfer sources was compared to data produced during sound power measurements at different ambient temperatures. The comparison revealed that the reference sound source cannot be uniquely characterized by a radiation type, although the aerodynamic sound production mechanism is related to dipole behaviour. Instead, the radiation is a combination of different source orders as also revealed by the spherical harmonics energy distribution.

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