Sound power determination of realistic sources based on the substitution method and sound intensity measurements

Spyros Brezas[1], Christian Bethke[2], Volker Wittstock[3]

[1,2,3] *Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, E-Mail:spyros.brezas@ptb.de*

Introduction

The determination of the widely used quantity of sound power is performed up to present by measuring the field quantity of sound pressure or sound intensity. This way, the effects of the surrounding environment are highly influential at low frequencies and for sound sources of tonal characteristics. The use of the substitution method [1] is assumed to be able to eliminate such effects providing the free field sound power determination. This contribution presents results for the sound power of realistic sources based on sound intensity measurements. The influence of the measurement surface was studied along with the influence of the surrounding environment. For each parameter study, the related uncertainty is also provided.

Substitution method

The substitution method for the determination of the free-field sound power level of source S' based on the known free-field sound power level of source S and on sound intensity measurements is described by the following equation:

$$L_{W,S'} = L_{W,S} + \overline{L}_{I,S'} - \overline{L}_{I,S} \qquad (1)$$

where $L_{W,S'}$ and $L_{W,S}$ is the free-field sound power level of the source S' and S respectively. $\overline{L}_{I,S'}$ and $\overline{L}_{I,S}$ is the time and surface averaged sound intensity level of each source.

Within the scope of a project financed by the European Metrology Research Programme, PTB assembled a primary sound source (vibrating piston) of known free-field sound power [2]. The dissemination of the free-field sound power can be performed by the use of a transfer source. Based on previous studies [3], an aerodynamic reference sound source was used. The sound power determination of realistic sources required the application of the substitution method twice. Firstly, for the determination of the free-field sound power of the transfer source and secondly, for the determination of the free-field sound power of the realistic sources.

Figure 1: Sources used in this study. Left to right: primary source, transfer source, fan, air compressor and vacuum cleaner.

Three realistic sources were chosen, namely a fan, an air compressor and a vacuum cleaner, since they provide spectral content variety. Figure 1 shows the primary source, the transfer source and the realistic sources used for this study.

The sound intensity was calculated by FFT measurements according to:

$$I_n(\omega) = \frac{1}{\omega \rho \Delta x} \mathrm{Im}\left[S_{p1p2}(\omega)\right] \qquad (2)$$

where ω is the angular velocity, ρ the air density, Δx the intensity probe spacer length and $\mathrm{Im}\left[S_{p1p2}(\omega)\right]$ the imaginary part of the cross spectrum of the intensity probe microphone signals [4]. For the coverage of the frequency range between 20 Hz and 10 kHz, two spacers of 9 & 71 mm length were used.

The primary source emitted a multi-sine signal with a frequency resolution of 3.125 Hz, which was also used for the FFT analysis. A uniform time window was used for the primary source measurements. For the random signal of the transfer source, a Hanning window was used.

Influence of the measurement surface shape

The influence of the measurement surface on the sound intensity level measurement was studied in PTB's hemianechoic room. A hemispherical surface of various radii was covered by PTB's scanning apparatus [5] along with a twelve-point box shaped surface with dimensions 2.5 m x 2.5 m x 1.5 m. Figure 2 shows the sound power level spectrum of the air compressor directly calculated after sound intensity measurements for both measurement surfaces. Its tonal content is apparent in the FFT spectrum.

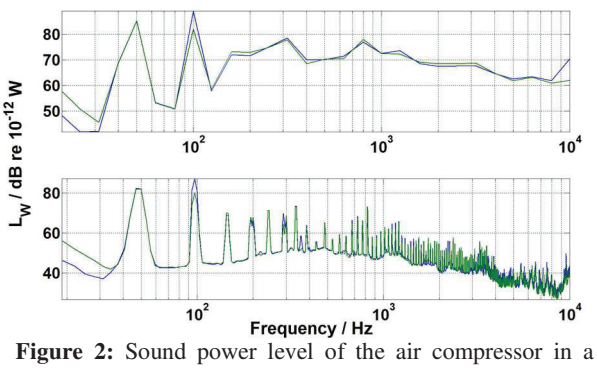

Figure 2: Sound power level of the air compressor in a hemianechoic room for hemispherical (blue) and box shaped measurement surface (green). Top: one-third octave band analysis. Bottom: FFT analysis (3.125 Hz resolution).

Figure 3 shows the sound power level differences between the levels determined after applying the substitution method and the levels directly calculated by the sound intensity measurements for both measurement surfaces and all realistic sources.

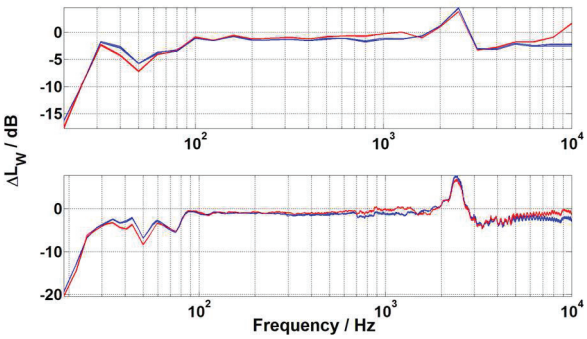

Figure 3: Sound power level differences of realistic sources determined by the substitution method and directly calculated for hemispherical (blue) and box shaped (red) measurement surfaces. Top: one-third octave band analysis. Bottom: FFT analysis (3.125 Hz resolution).

Figure 3 clearly shows that the sound power levels determined by the substitution method are lower than those directly calculated from sound intensity measurements below 90 Hz. Under the assumption that eq. (1) holds this means that the sound power level which is emitted into PTB's hemianechoic room (cut-on frequency about 90 Hz) is considerably larger than the sound power level that would be emitted by the same sources into a free field. It is furthermore to be mentioned that insufficiencies of PTB's primary source cause the deviations at frequencies above 2 kHz. It also shows that the sound power level differences are nearly the same for all sources (3 blue and 3 red lines in each graph) per measurement surface.

Influence of the surrounding environment

For the influence of the surrounding environment, sound intensity measurements were performed in three different rooms apart from the hemianechoic room. The rooms were of different volumes and absorption (Table 1). The hard walled room 2 was used for two measurements, one without and one with additional absorption.

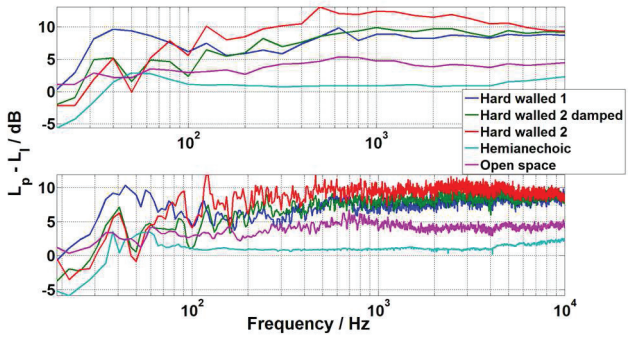

Figure 4: Mean sound pressure minus intensity index for measurements at different rooms. Top: one-third octave band analysis. Bottom: FFT analysis (3.125 Hz resolution).

Table 1: Volumes of measurement rooms

Room	Volume (m^3)
Hard walled 1	50
Hard walled 2	50
Hemianechoic	190
Open space	-

For the sound intensity measurements outside the hemianechoic room, the box shaped measurement surface was applied. The pressure - intensity index carries information about the properties of the source and the sound field on the measurement surface [4]. The covered range up to 13 dB indicates a large variety of field situations (Figure 4) for the mean index of all realistic sources in all rooms.

Figure 5 shows the sound power level of the fan determined by direct calculation based on the sound intensity measurements and after applying the substitution method.

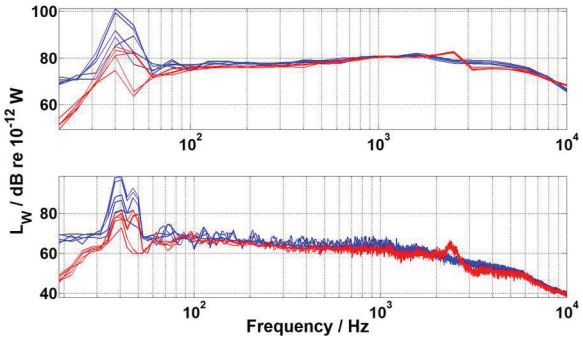

Figure 5: Sound power level of the fan determined by direct calculation (blue) and by the substitution method (red) in various rooms. Top: one-third octave band analysis. Bottom: FFT analysis (3.125 Hz resolution).

The mean sound power level differences for all sources between the substitution method and the direct method for each room are presented in figure 6.

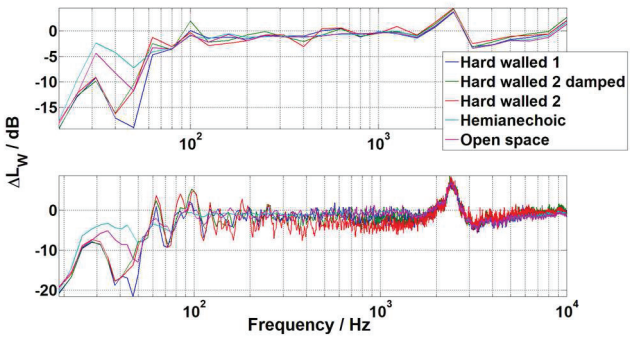

Figure 6: Sound power level differences of realistic sources between the substitution method and direct calculation for various surrounding environments. Top: one-third octave band analysis. Bottom: FFT analysis (3.125 Hz resolution).

In accordance to figure 3, figures 5 and 6 show the lower levels provided by the substitution method at low frequencies. The influences of the insufficiencies of the primary source are also apparent in figure 6.

Uncertainty due to the measurement surface

For the calculation of the uncertainty imposed by the influence of the measurement surface, the uncertainty of all substitution method applications are required. The calibration of the transfer source (TS) under calibration conditions using the primary source data (PS) can be expressed by:

$$L_{W,\mathrm{TS,cal}} = L_{W,\mathrm{PS}} + L_{I,\mathrm{TS,cal}} - L_{I,\mathrm{PS}} - 10\lg\frac{B_{\mathrm{TS,cal}}}{B_{\mathrm{PS}}}\,\mathrm{dB} + 5\lg\frac{T_{\mathrm{TS,cal}}}{T_{\mathrm{PS}}}\,\mathrm{dB} - L_{\mathrm{Hanning}} \quad (3)$$

The related uncertainty is given by:

$$u^2\left(L_{W,\mathrm{TS,cal}}\right) = u^2\left(L_{W,\mathrm{PS}}\right) + u^2\left(L_{I,\mathrm{TS,cal}} - L_{I,\mathrm{PS}}\right) + \left[\frac{10\,\mathrm{dB}}{\ln 10}\frac{B_{\mathrm{PS}}}{B_{\mathrm{TS,cal}}}u\left(\frac{B_{\mathrm{TS,cal}}}{B_{\mathrm{PS}}}\right)\right]^2 + \left[\frac{5\,\mathrm{dB}}{\ln 10}\frac{T_{\mathrm{PS}}}{T_{\mathrm{TS,cal}}}u\left(\frac{T_{\mathrm{TS,cal}}}{T_{\mathrm{PS}}}\right)\right]^2 \quad (4)$$

The term L_{Hanning} is introduced due to the different time window applied for the PS and the TS measurements. It has been experimentally found to be 1.78 dB. The variations in the environmental conditions (atmospheric pressure B and temperature T) were calculated and pose a negligible uncertainty contribution. According to the above, equation 4 reduces to:

$$u^2\left(L_{W,\mathrm{TS,cal}}\right) = u^2\left(L_{W,\mathrm{PS}}\right) + u^2\left(L_{I,\mathrm{TS,cal}} - L_{I,\mathrm{PS}}\right) \quad (5)$$

The uncertainties related to the in-situ measurements of the TS were calculated [6]. The variations of both environmental and operational conditions yielded a negligibly small uncertainty. Based on that, the uncertainties of the measurement of the transfer standard under calibration conditions equal the uncertainties of the in-situ measurements.

The substitution method for the sound power determination of the realistic sources – devices under test (DUT) carries another uncertainty contribution, described by:

$$u^2\left(L_{W,\mathrm{DUT,situ}}\right) = u^2\left(L_{W,\mathrm{TS,situ}}\right) + u^2\left(L_{I,\mathrm{DUT,situ}} - L_{I,\mathrm{TS,situ}}\right) = u^2\left(L_{W,\mathrm{TS,situ}}\right) + u^2\left(\Delta L_I\right) \quad (6)$$

The uncertainty due to the sound intensity level difference is determined by:

$$u^2\left(\Delta L_I\right) = \frac{\frac{1}{n-1}\sum\left(\Delta L_{I,i} - \overline{\Delta L_I}\right)^2}{n} \quad (7)$$

where n is the number of measurement positions on the box shaped measurement surface. The use of the sound intensity level difference in equations (3)-(7) is expected to provide cancellation of intensity probe insufficiencies.

Figure 7 shows the uncertainties of the sound power level for the vacuum cleaner based on the substitution method for the different measurement surfaces as described above. The combined uncertainty for the measurements over a hemisphere is lower than that over a box. The former is mainly affected by the transfer source sound power uncertainty, while the latter by the sound intensity level difference uncertainty.

Figure 8 shows the uncertainty contributions for the sound power level of the fan measured in hard walled room 1. As previously, the main contributing factor to the combined uncertainty is the uncertainty of the sound intensity level difference.

For the validation of the proposed uncertainty budget, the following procedure was performed. For each source measurement set (e.g. the fan sound power level after substitution in all measurement rooms) the level difference between the mean value and each value was calculated as:

$$\Delta L_{W,i} = \overline{L}_W - L_{W,i} \quad (8)$$

The difference was compared to the uncertainty interval for 95% confidence ($\pm 2U$). Figures 9 and 10 show the sound power level difference according to equation 8 for all realistic sources measured at the open space.

Figures 9 and 10 reveal that the proposed uncertainty budget covers the deviations seen in the measured data except for the frequency range around 50 Hz. At these frequencies, it is assumed that a vibration excitation of the floor occurred in some of the rooms.

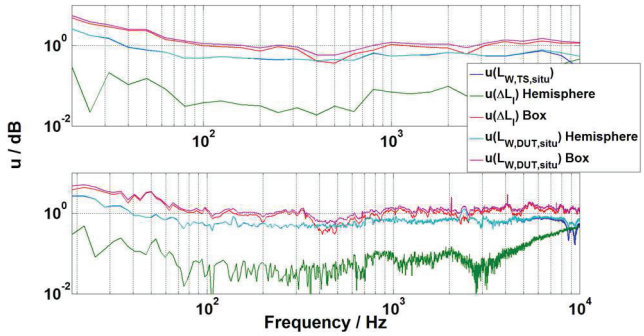

Figure 7: Uncertainty components for the sound power determination of a vacuum cleaner after the substitution method for different measurement surfaces. Top: one-third octave band analysis. Bottom: FFT analysis (3.125 Hz resolution).

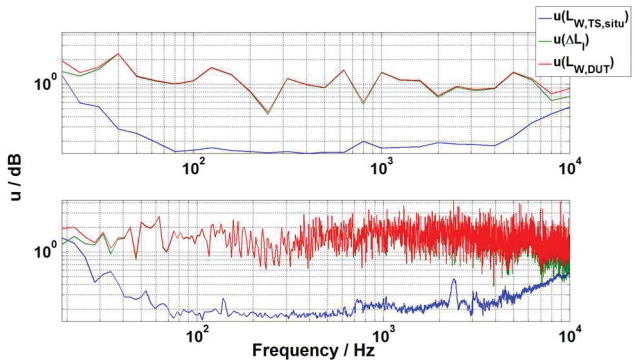

Figure 8: Uncertainty components for the sound power determination of a fan after the substitution method at hard walled room 1. Top: one-third octave band analysis. Bottom: FFT analysis (3.125 Hz resolution).

Conclusions

For the evaluation of the sound power determination after the substitution method based on sound intensity measurements, three realistic sources were measured. The measurements included variations in the measurement surface and the surrounding environment (rooms of different volume and absorption).

The comparison of the sound power levels determined by applying the substitution method and the directly derived levels reveals the lower influence of the surrounding environment at low frequencies for the former levels.

The uncertainty of the substitution method was also determined. The uncertainty of the sound intensity level difference plays the most significant role for variations in the surrounding environment for the box shaped measurement surface. For sound intensity measurements over a hemisphere, the uncertainty of the transfer source is the most important factor.

The evaluation of the proposed uncertainty reveals the coverage of the variations in the sound power levels after the substitution method.

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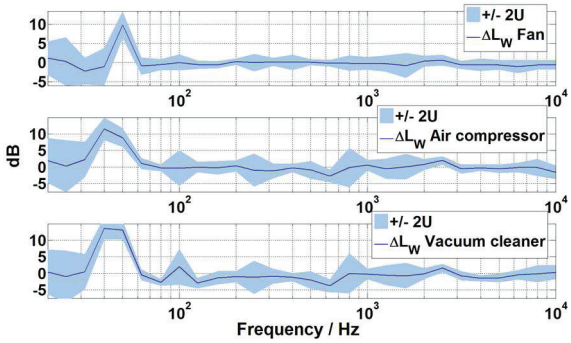

Figure 9: Sound power level difference and expanded uncertainty for various sources measured at open space. One-third octave band analysis.

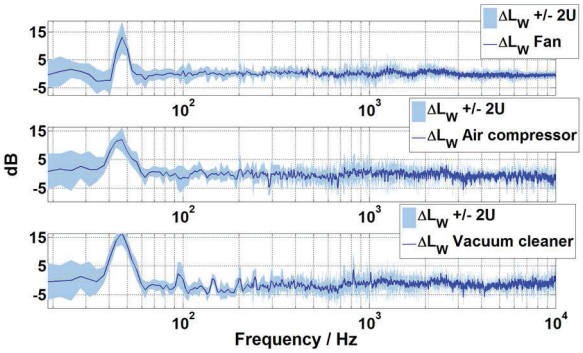

Figure 10: Sound power level difference and expanded uncertainty for various sources measured at open space. FFT analysis (3.125 Hz resolution).

Literature

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