ABSTRACT
It is not a secret that the application of the current sound power level measurement standards, even of the same grade of accuracy, leads to different results both under laboratory and even more under in situ conditions.
To gain a much deeper insight into the major parameters causing differences in the determined sound power levels when applying different methods sound power levels of different sound sources were determined under both laboratory conditions and in situ conditions.
The paper compares the measurement results gained from measurements with varying parameters such as different enveloping surface shapes, different measurement probe position arrangements and sound field scanning methods both for sound intensity respectively sound pressure. These investigations were carried out under laboratory conditions determining the sound power level of a transfer standard source, a small compressor and a model machine.
The application of a transfer standard source referring to the primary standard “unit Watt” was done on purpose as to qualify the measurement set-ups and to allow traceability of the determined sound power levels of machines to the primary standard.
The analysis of the measurement results helps to identify main issues and to support the idea to improve the standards in respect to a more reliable application of the different methods in practice.

Keywords: sound power level, transfer standard source, sound power measurement standards, traceability

1. TRACING MACHINES TO THE PRIMARY STANDARD “UNIT WATT” APPLYING A TRANSFER STANDARD SOURCE

The establishment of a primary source generating a defined airborne sound power traceable to the basic units m, kg, s would allow to get a clearer view on the achievable accuracy of sound power level determinations of real noise sources like machines in situ. This would offer to better adapt the applied measurement method to the specific measurement task. Thus e.g. the radiation pattern of the source and the environmental as well as background noise conditions during measurement could play an important role in adequately adapting the measurement method in such a way, that the effort would be minimized without reducing the measurement accuracy at the same time.

The formula to be used to take reference to the primary source is based on the simple relation for the sound power level \( L_W \) determined from averaging sound pressure levels \( L_p \) at several positions on the measurement surface area \( S \) enveloping the source.

\[
L_W = L_p + 10 \log \frac{S}{1m^2} \quad \text{dB (1)}
\]

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Therefore the sound power level of the primary source (ps) can be written as

$$L_{W,ps} = \frac{L_{p,ps}}{10} + 10 \log \frac{S}{1m^2} \text{ dB}$$  \hphantom{(2)} \tag{2}

and the sound power level of any machine (m), assuming the application of the same measurement surface and a measurement in the same surrounding (equal background and environmental conditions), finally as

$$L_{W,m} = \frac{L_{p,m}}{10} + 10 \log \frac{S}{1m^2} \text{ dB}$$  \hphantom{(3)} \tag{3}

Comparing equation (2) and (3) leads to

$$L_{W,ps} - \frac{L_{p,ps}}{10} = L_{W,m} - \frac{L_{p,m}}{10} \text{ dB}$$  \hphantom{(4)} \tag{4}

thus relating the sound power level of any machine to the one of the primary source. The final relation can then be written as

$$L_{W,m} = L_{W,ps} + 10 \log \frac{\sum_{i=1}^{N} 10^{0.1L_{p,m,i}}}{\sum_{i=1}^{N} 10^{0.1L_{p,ps,i}}} \text{ dB}$$  \hphantom{(5)} \tag{5}

on condition, that the partial areas of the measurement surface are of equal size.

Finally considering the difference between the two sound power levels described by

$$L_{W,m} - L_{W,ps} = 10 \log \frac{\sum_{i=1}^{N} 10^{0.1L_{p,m,i}}}{\sum_{i=1}^{N} 10^{0.1L_{p,ps,i}}} \text{ dB}$$  \hphantom{(6)} \tag{6}

one may assume that this difference stays constant even considering measurements under different environmental conditions. However, it is clear that this assumption is only realistic if the “true” sound power level of each source is basically independent from the environment. This requires first of all that any known errors during the measurement can be neglected. These are the nearfield error (angle and impedance error) and the error due to the limited number of measurement positions on the enveloping surface basically related to the non-uniform radiation of the source.

Starting with the rearranged equation (4) now reading

$$L_{W,m} - L_{W,ps} = \frac{L_{p,m}}{10} - \frac{L_{p,ps}}{10} \text{ dB}$$  \hphantom{(7)} \tag{7}

and assuming a reliable correction for background noise and the environment, a comparison between measurements in freefield (ff) and in situ (is) leads to the assumption

$$L_{W,m,ff} - L_{W,ps,ff} = L_{W,m,is} - L_{W,ps,is} \text{ dB}$$  \hphantom{(8)} \tag{8}

Thus, it can be expected that the differences

$$\Delta L_{W,ff} = L_{W,m,ff} - L_{W,ps,ff} \text{ and } \Delta L_{W,is} = L_{W,m,is} - L_{W,ps,is}$$  \hphantom{(9)} \tag{9}

are equal so that

$$\Delta L_{W,is} - \Delta L_{W,ff} = \Delta L = 0$$  \hphantom{(10)} \tag{10}

The fulfillment of equation (10) would support the basic assumption, that the sound power level of a sound source is independent from the environment. However, we already know that this is not true. One simple example is the change of the sound power level of a small sound source when lifted to different heights above a reflecting floor (see reference 1).
In order to get an additional indication that the sound power of a source placed into different environments is not constant, measurements were carried through to check the validity of equation (10). Owing to the yet unavailable primary source a secondary standard, the also for practicability in future more frequently applied transfer standard source (TSS) was used as reference and an air compressor as real machine. Because of its properties the reference sound source from Brüel & Kjær, type 4204 was considered to be appropriate as TSS and is therefore used in this project.

The sound power levels of both sources were determined under in situ conditions – in a small workshop with different machine tools with a negligible background noise - and additionally under free field conditions - in a semi-anechoic chamber. For both sound sources the same measurement arrangement was applied. As measurement surface a parallelepiped was chosen with a measurement distance of 1 m related to the compressor. Nine measurement positions according to ISO 3744:2010 (2) were used. The dimensions of the parallelepiped measurement surface were (length x width x height) 2.60 m x 2.35 m x 1.63 m. The measurements were done under repeatability conditions. That means the same measurement equipment was repeatedly used by the same staff in the respective environment, 9 measurements on 3 days for the industrial environment and 15 measurements on 5 days for the semi-anechoic chamber.

Figure 1 shows the difference of the deviations of sound power level determinations $\Delta L_{W,IS} - \Delta L_{W,FF}$ as one third octave band frequency spectrum.

![Figure 1](image_url)

Figure 1 – Difference of the deviations of sound power level determinations of a compressor and the TSS measured in the workshop and under free field conditions

Obviously the difference $\Delta L_{W,IS} - \Delta L_{W,FF}$ reaches values up to 3.6 dB at specific frequencies bands. Fortunately, considering the total A-weighted respectively the total unweighted sound power level (see also table 2) the differences get much smaller, resulting in 0.1 or -0.7 dB only.

In a second set of measurements a much larger source was used, simulated by a model machine. The model machine (MM, figure 2) consists of an aluminum profile construction including 2 mm aluminum sheets with the dimensions 2.80 m x 1.12 m x 1.73 m (length x width x height). Underneath this construction two RSS type B&K 4204 were placed as exciting sound sources causing the outer aluminium sheets to radiate sound.
Again the MM and the TSS were operated in both a semi-anechoic chamber to reach free field conditions and in different industrial environments. The measurements were carried out under a parallelepiped measurement surface with a measurement distance of 1 m related to the MM and with nine measurement positions. The measurements were done under repeatability conditions. The number of measurements in the semi-anechoic chamber was 15 on 5 days and 9 on 3 days for the industrial environments.

The data gained from the sound power measurements in different environments denoted with R6, R7, R9 and R10 (see table 1) are similar for the different environments at first glance. But the final comparison (see figure 3) again shows that the differences at each frequency band are not the same within the different in situ situations. Considering the A-weighted respectively the linear sound power level (see also table 2) the differences are up to -1.4 or -1.3 dB.

The complete set of results is listed in table 2 clearly showing that the expected value of $\Delta L$ is not zero!

Table 1 - Specifications of the measurement environments

<table>
<thead>
<tr>
<th>Room</th>
<th>Floor area</th>
<th>Room height</th>
<th>Short description</th>
<th>Position of the MM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel hall, DASA: Working World Exhibition in Dortmund</td>
<td>2876 m²</td>
<td>10.8 m … 17.3 m</td>
<td>Large hall, partly with equipment and installations</td>
<td>centric</td>
</tr>
<tr>
<td>Energy hall, DASA: Working World Exhibition in Dortmund</td>
<td>423 m²</td>
<td>10.8 m</td>
<td>Small hall with a high ceiling, more or less empty</td>
<td>centric</td>
</tr>
<tr>
<td>Writing desk, occupational safety, DASA: Working World Exhibition in Dortmund</td>
<td>171 m²</td>
<td>3.2 m … 7.0 m</td>
<td>Box shaped room, slightly contorted, partly with equipment and installations</td>
<td>centric</td>
</tr>
<tr>
<td>Refreshment area, building 1 of the BAuA in Dortmund</td>
<td>210 m²</td>
<td>2.3 m … 3.7 m</td>
<td>Box shaped room, slightly contorted, on one side slanted walls</td>
<td>centric</td>
</tr>
</tbody>
</table>
Figure 3 - Difference of the deviations of sound power level determinations of a model machine and the TSS measured in different environments (see table 1) and under free field conditions.

Table 2 - Difference $\Delta L_{W, is} - \Delta L_{W, ff}$ of the total sound power level of the measured model machine respectively compressor and the TSS under in situ and free field conditions.

<table>
<thead>
<tr>
<th>Room</th>
<th>Compressor</th>
<th>Model machine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Workshop</td>
<td>R6 R7 R9 R10</td>
</tr>
<tr>
<td>$\Delta L_{WA}$</td>
<td>-0.7</td>
<td>-0.3 -0.2 -1.3 -1.3</td>
</tr>
<tr>
<td>$\Delta L_{W}$</td>
<td>0.1</td>
<td>-0.8 -0.1 -1.4 -0.3</td>
</tr>
</tbody>
</table>

The reasons for these results are various and can have many different origins. Besides the assumption that the sound power level of a source is not constant when moving a source from a free field situation into an in situ situation it is necessary to first consider whether the applied measurement method really leads to the sound power level of the source in the respective environment. Consequently the environmental correction methods have to be checked thoroughly and furthermore the influence of the different directivities of the compared sources.

2. MEASUREMENT RESULTS

2.1 SOUND POWER LEVEL OF THE TRANSFER STANDARD SOURCE

Within the EMRP-project „Realisation, Dissemination and Application of the Unit Watt in Airborne Sound“ the Federal Institute for Occupational Safety and Health (BAuA) applied several different measurement arrangements for determining the sound power level of different sources by both sound pressure and sound intensity measurements under free field conditions in a semi-anechoic room (see figure 4). Results from the sound power level determination of the TSS (B&K 4204) are presented to get an idea on the typical differences related to the different standardised methods. This comparison shall serve the purpose to identify some main issues for improving the standards.
shows the difference $\Delta L_{TSS} = L_{W,TSS} - L_{W,TSS,\text{reference}}$ for the respective measurement arrangements with $L_{W,TSS,\text{reference}}$ the sound power level of the TSS determined from measurements of the sound pressure at 20 measurement positions on a hemisphere with a radius of 2 m. This measurement set-up was chosen as reference due to a negligible angle and impedance error and due to a frequency range is less restricted compared to a sound intensity probe with a specific spacer. The reference cube enclosing the TSS has the dimensions 0.3 m x 0.3 m x 0.3 m and the measurement positions comply with those stated in table B2 of ISO 3744:2010 (2).

Figure 4 - Semi-anechoic measurement room of the BAuA, sound power level determination of the transfer standard source (B&K 4204) under a hemispherical measurement surface with a radius of 3 m and 20 measurement points

Figure 5 shows the results in 3 different sections, the upper one representing the sound power level determined by sound pressure level measurements at different measurement positions on different enveloping surfaces, the mid one doing equivalent measurements but using the sound pressure scanning method on partial surfaces by extraction of the sound pressure from an intensity probe and finally by measurement of the sound pressure level by microphones on specific paths. The lowest section of the figure shows results from pure sound intensity measurements (see also references 1, 3, 4).
Figure 5 – Transfer standard source, difference of the sound power level determined with different measurement arrangements and the reference measurement arrangement

<table>
<thead>
<tr>
<th>Parallelepiped</th>
<th>Cylinder</th>
<th>Hemisphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>d = 1 m (MM)</td>
<td>d = 1 m</td>
<td>d = 1 m</td>
</tr>
<tr>
<td>(Compressor)</td>
<td>r = 1.85 m</td>
<td>r = 2 m</td>
</tr>
<tr>
<td>d = 1 m</td>
<td>r = 1 m</td>
<td>r = 3 m</td>
</tr>
<tr>
<td></td>
<td>r = 4 m</td>
<td></td>
</tr>
</tbody>
</table>

Grey bars: application of single microphones
Blue bars: application of a sound intensity probe
Bar filled: discrete measurement positions
Bar hatched: measurement paths or scanning of partial surfaces

\[ \Delta L_{1/2} = L_{1/2,\text{source}} - L_{1/2,\text{reference}} \] in dB

Interpretation:
- **d**: measurement distance
- **r**: radius
- **(MM)**: referring to the model machine (dimensions of the reference parallelepiped: (length x width x height) 2.80 m x 1.12 m x 1.73 m)
- **(Compressor)**: referring to the compressor (dimensions of the reference parallelepiped: (length x width x height) 0.60 m x 0.35 m x 0.63 m)
- **MP**: (number of) measurement positions
- **Paths**: (number of) measurement paths
- **PS**: (number of) scanned partial surfaces
- Spacer for the intensity probe was 8.5 mm, unless otherwise indicated.

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The results show that the determined sound power level of a very stable sound source (TSS) is depending on the measurement procedure reaching a maximum span of difference values of 2.6 dB. In relation to the chosen (determination of the sound power level by sound pressure measurements on a hemispherical enveloping surface of $r = 2$ m with 20 measurement positions) reference value the maximum difference is 1.7 dB.

The deviations particularly result from systematic errors due to the chosen measurement points and paths arrangements and the related enveloping surfaces. The nearfield error (angle and impedance error) gets rather high for some measurement set-ups. Thus comparability of the results is not really given although measurements were done in an ideal environment allowing to forget environmental and background noise influences which are especially critical when using sound pressure level measurements. Measurement results in situ will therefore show an even larger spread of sound power levels as the required environmental as well as background noise corrections are the reason for additional errors. For real machines even these results will not be a good approximation of the maximum spread of determined sound power levels due to further critical parameters like inconstant operating and mounting conditions, inadequate application of the different methods etc..

Apart from one exception the sound power level determined from sound intensity measurements is about 0.5 to 1 dB less in respect to the reference level which was determined by measuring sound pressure.

The comparison of sound power levels gained from sound intensity measurements and those gained from scanned sound pressure levels, however captured from the intensity probe result in differences up to 1.5 dB.

Regarding the influence of the applied measurement surface the deviations for the hemispherical surface are the lowest followed by the deviations for the cylindrical surface. As expected the differences are highest for the parallelepiped surfaces, due to the angle error.

It is important to notice that the determination of the sound power level by using sound intensity measurements on 6 partial surfaces represents the grade of accuracy 1 of the standard ISO 9614-3:2002 (5). The arrangements with 64 partial surfaces represent the grade of accuracy 2 of the standard 9614-2:1996 (6). Significant differences in the determined sound power levels occurred for the 8.5 mm spacer but not for the 12 mm one! This may be explained by the reduced sensitivity of the smaller spacer at lower frequencies.

For sound pressure measurements applying a parallelepiped enveloping surface according to ISO 3744:2010 (2) rectangular as well as triangular partial surfaces were used. For the predominantly used parallelepiped measurement surface the 9 measurement positions arrangement (1 in the middle of each side area and 1 at each corner) was applied in order to compare it with the 10 measurement points arrangement (1 in each centre of gravity for the smallest number of 10 partial triangular surfaces). Whereas the 9 measurement positions is not in line with physics as the corner measurement points do not represent an energy flow through a defined area (intensity) the 10 points arrangement is physically correct. However the result shows that the determined sound power level using the 9 measurement point arrangement is significantly closer to the reference sound power level. The in practice for economic reasons preferred 5 measurement points arrangement, representing the sound energy flow through each side area of the parallelepiped, results in even higher deviations compared to the reference sound power level. In the latter case the sound power level is significantly overestimated, in the example in figure 5 about 1.6 dB.

Lower deviations were found for the sound power level determined by using a cylindrical enveloping surface. This, although the measurement point arrangement is the same as the five measurement points one on a parallelepiped enveloping surface. Thus there are only two possibilities explaining the smaller differences. The first reason is the reduced magnitude of the enveloping surface adding a smaller quantity to the average sound pressure level on that surface. The second reason may be the radiation pattern of the TSS which seems to be better adapted by a cylindrical measurement surface. No differences were found for this uniformly emitting sound source under a hemispherical measurement surface with 20 or 10 measurement points.

### 2.2 SOUND POWER LEVEL OF THE COMPRESSOR AND THE MODEL MACHINE

In figure 5 some results determined for different measurement set-ups are shown allowing the comparison of the difference $\Delta L = L_W - L_{W,\text{reference}}$ gained from measurements of different sound sources - the TSS, a small air compressor and the model machine.
Figure 5 – Difference of the sound power levels determined from applying different measurement arrangements on different sound sources in relation to the reference measurement arrangement.

\[ L' = |L_{\text{ref}} - L'_{\text{meas}}| \text{ in dB} \]

**Interpretation:**
- Grey bars: application of single microphones
- Blue bars: application of a sound intensity probe, Spacer 8.5 mm

**Results:**
The results show that there is a large spread of the determined sound power levels in relation to the reference sound power defined for each source.

<table>
<thead>
<tr>
<th>Source Type</th>
<th>Measurement Distance</th>
<th>Measurement Positions</th>
<th>Sound Power Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parallelepiped</strong></td>
<td>d = 1 m</td>
<td>22 MP (MM: 40 MP)</td>
<td>9 MP, 5 MP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hemisphere</strong></td>
<td>r = 2 m (MM: r = 3 m)</td>
<td>20 MP (reference value)</td>
<td>5 MP, 20 MP, 10 MP</td>
</tr>
<tr>
<td><strong>Transfer standard source (TSS)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Compressor</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Model machine (MM)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Definitions:**
- d: measurement distance
- r: radius
- MM: model machine
- MP: (number of) measurement positions
- Grey bars: application of single microphones
- Blue bars: application of a sound intensity probe, Spacer 8.5 mm
3. MEASURING EFFORT

Besides the measurement uncertainty the measuring effort, especially the measurement equipment required and the time needed for the measuring procedure, should be taken into consideration when deciding on the application of measurement standards. The measurement equipment costs are determined by the extent of the needed measurement system including the kind (microphones/intensity probes) and number of sensors, appropriate calibrators and additional accessories, hardware for positioning the sensors and further equipment as e.g. a rotary plate. The time differs with the sampling (shape of the enveloping surface, number of measurement positions, measurement points or scanning) including the preparation of the measurement arrangement. For an intensity probe a more precise usually manually guided orientation in relation to the measurement surface is needed compared to the use of microphones – at every position or on each path. A large enveloping surface makes the measurement set-up more expensive and the measurement even more difficult. Finally the effort for the analysis is to be taken into account too.

The measuring effort for the measurement arrangements discussed in this paper differs significantly. The determination of the sound power level from sound pressure measurements at five positions on a parallelepiped surface is the simplest arrangement. But the sound power level is overestimated. The positioning of microphones on a hemisphere is more difficult but leads to better results. Determining the sound power level by intensity measurements is basically more precise compared to sound pressure measurements but it is more expensive too.

4. CONCLUSIONS

The current results show that the sound power level of a source is not only depending on the applied measurement setup but even worse on the reaction of the source in respect to the environment in which the machine is placed. It seems that at least under specific cases the sound power level of a source is depending on the environment. This is basically nothing new but has constantly been ignored by the standard drafters. Fortunately at least the A-weighted values are not showing too large differences.

Nevertheless it will therefore be necessary to carefully improve both the measurement methods and the knowledge under which circumstances the sound power level of a source under free field conditions can be compared with the one gained in rooms!

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