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Is the airborne sound power level of a source unambiguous?

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ABSTRACT

Sound power levels are used as key parameters describing the noise emission of machines in the European Machinery Directive 2006/42/EC (1) and the Outdoor Equipment Directive 2000/14/EC (2). The purpose is to require machine manufacturers to provide noise emission declarations thus allowing potential purchasers to buy quiet. To support this approach for noise reduction noise emission measurement standards providing measurement methods for determining the sound power level have been constantly developed on ISO level since many years. Although the sound power level methods described in these standards are based on different concepts they claim to result in comparable sound power levels of a source when the grade of accuracy of the standard is the same. However, it is known for long that this is not really the truth. In order to get more information on this differences systematical measurements were carried out on a reference sound source using sound pressure and sound intensity discrete measurement positions as well as scanning methods on different surfaces and at different distances from the source under free-field conditions. First results of a respective EMRP project are given in this paper.

Keywords: Sound power level, sound intensity scanning, sound pressure scanning

1. INTRODUCTION

Legal requirements especially in Europe aim at a transparent market on the noise emission of machines. The idea is to allow purchasers of machines to buy comparatively quiet machines in order to reduce the noise exposure at work places and in the neighborhood. Hence, European Directives such as the Machinery Directive (MD) 2006/42/EC and the so called “Outdoor” (OED) Directive 2000/14/EC deal with machine noise emissions, requiring manufacturers to provide information on the airborne sound radiated by the machine. Therefore the major parameter of noise emission, the sound power level, is required to be given according to the MD in the instructions or sales literature, depending on the value of the emission sound pressure level, respectively the machine has to be marked on the outer surface according to the OED with a label providing an information about the guaranteed sound power level. As the OED additionally requires to observe noise emission limit values for 22 kinds of machines, the uncertainty of measured sound power levels is of great importance. Moreover the MD is requiring to provide information on the uncertainty of the determined sound power levels since its last revision in 2006.

To determine the sound power level measurement methods had been developed since now more than 40 years. They are published in a set of EN ISO standards which are based on different methods using sound pressure or sound intensity as the measured input data. Unfortunately, the application of these different methods shows systematic deviations that cannot be quantified due to a missing reference method. This applies not only for measurements of the sound power level, under well-controlled laboratory conditions, but especially under in situ conditions where the influence of environmental and background noise conditions of the measurement location needs to be clearly determined. However, this is not yet possible because the traceability to a primary standard is missing. Therefore a European metrology research project (EMRP, Realization, dissemination and application of the unit watt in airborne sound) is currently working on the development of a primary standard for the realisation of the unit watt in airborne sound. Moreover it will be investigated whether a system for the dissemination of the unit watt can be developed using appropriate transfer standards e.g. such as existing aerodynamic reference sound sources.

The BAuA takes an active part in this project consisting of the collaboration of several European metrology institutes, however concentrates on the application of such a transfer standard as reference for the use under practical conditions. Therefore the BAuA concentrates on the comparison of measurement position arrangements, environmental correction methods and measurement surface shapes as well as on the comparison of sound intensity and sound pressure measurements at discrete points or using scanning methods in both cases for the determination of the sound power level. The aim is to analyze and quantify the uncertainties associated with the different sound power measurement methods, including the qualification procedures of the measurement environment applied under in situ conditions. This shall lead to improvements of the basic measurement methods with respect to simplification and traceability.

That this is urgently necessary can be derived from the result of the joint European ADCO Machinery “NOMAD” project (3) which has shown that 80% of all noise declarations are not complying with the Machinery Directive and the “Outdoor”- Directive. One of the identified reasons is that the basic noise emission measurement standards are seen as being very complex and expensive, resulting in a great reluctance of manufacturers and even test houses to carefully apply the methods. Simplification of their application is therefore the order of the day. However, simplifying the basic measurement methods requires a good knowledge about all the parameters which have an influence on the measurement result.

2. Measurements

2.1 Measurement environments, sound sources and measurement equipment

The following first results were gained from measurements carried through in the large hemi free-field room (figure 1) of the acoustical laboratory of the BAuA. The measurements were done by the same staff applying the same measurement equipment determining the sound power level of a single B&K reference sound source (RSS) type B&K 4204. For data processing a multi-channel B & K PULSE platform for real time noise analysis was used, allowing the simultaneous measurement and analysis of acoustic signals on the required 20 channels. The measurement equipment was calibrated before and after each measurement.

The measurement environment chosen was a hemi free-field measurement room resiliently mounted and decoupled from the main laboratory building by steel springs with a system Eigen frequency of 3 Hz. It’s clear dimensions are (l x w x h) 15 m x 9.5 m x 6.4m with absorption material made from mineral wool, shaped as cubes of different size and suspended on steel wires. The absorption depth is 1.4 m.

In order to check the necessity of applying correction factors K_0, K_1, K_2 when determining sound power levels prechecks were performed.

- Meteorological correction K0: To minimize the effects of adverse meteorological conditions the temperature and static pressure in the measurement room was constantly checked. It was found that during the measurements changes of temperature and static pressure were so small that any influence would result in changes of the measured sound power levels at a maximum of 0.1 dB.

- Background noise correction K1: Figure 2 shows a spectrum of the typical background noise sound pressure level spectrum. Apparently the background noise is dominant by the instrumentation noise and thus not only fulfilling the absolute criteria for the maximum background noise levels in a test room as given in table 1 of ISO 3745: 2010 (4), but also the general one requiring a difference of at least more than 10 dB between the noise of the source and the background noise in each frequency band.

- Environmental correction K2: Shortly before the start of the project the hemi free-field room was checked according to ISO 26101:2012 (5). The results showed that for broad band random noise the room complies with the requirements on hemi free-field rooms of annex A of ISO 26101 for transverses of maximum 4.4 m (equal to a radius from a point at the center of the room) even at the 1/3 octave band frequency of 50 Hz. Except for sinusoidal signals some deviations from the 1/r law occurred especially at greater distances from the source. However, as the measured RSS generates broadband sound an environmental correction seems to be not required in the frequency range of interest.

Figure 1 Hemi free-field room used for the sound power level determination

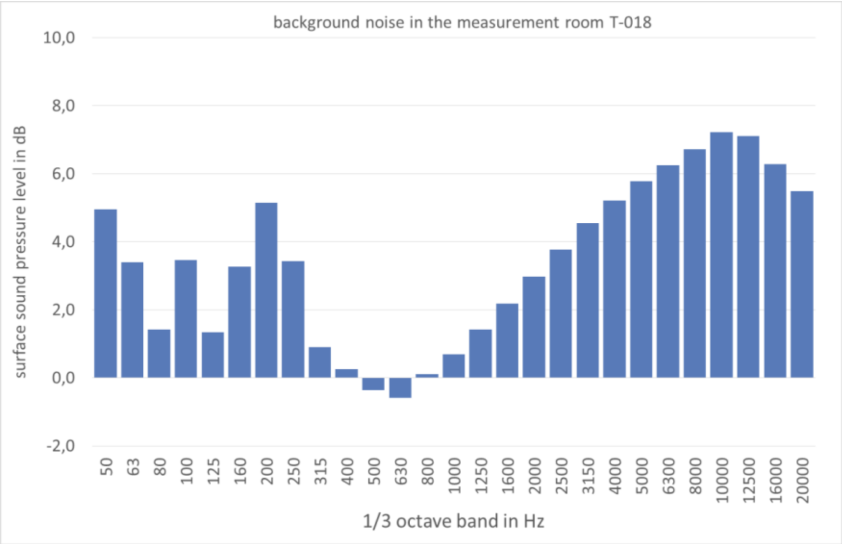

Figure 2 Background noise in terms of the average sound pressure level on the hemispherical respectively on the hemispherical measurement surface in the hemi free-field room determined by using the B&K "Pulse" analyzer

2.2 Measurement basis

It is well known that the sound power P respectively the time averaged sound energy flow can be described using the Gauss´ theorem and the sound intensity vector $\vec{I}$ giving

$$\oiiint_V \operatorname{div}\vec{I}\,dV = \oiint_S \vec{I}\,d\vec{S} = \oiint_S I_n dS = P. \qquad (1)$$

In consequence the sound power is resulting from integrating the normal component of the sound intensity I_n on an imaginary surface enveloping the sound source.
Assuming α to be the angle between $\vec{I}_n$ and $\vec{I}$ we get

$$|\vec{I}_n| = |\vec{I}|\cos\alpha = \overline{p|\vec{v}_n|}^t \cos\alpha = \overline{pv_n}^t \cos\alpha \qquad (2)$$

From this formula two basic approaches to determine the sound power can be derived. The first approach is based on the so called far field assumption claiming α to be zero thus I_n and v_n to be parallel like in a plane wave. In this case v_n is proportional to p with the proportionality factor given by the inverse of the characteristic acoustic impedance ρc. This leads to

$$I_n = \frac{\tilde{p}^2}{\rho c} \tag{3}$$

The right part of the formula 1 can then be approximated as follows

$$P = \oiint_S I_n dS \approx \frac{1}{\rho c} \sum_{i=1}^{N} \tilde{p}_i^2 \Delta S_i \tag{4}$$

leading under the assumption of equal partial areas to the well-known free field sound power equation

$$L_W = \overline{L_p} + 10\log\frac{S}{1m^2} \text{ dB.} \tag{5}$$

the basis of the sound power level determination from sound pressure p measurements on a surface S enveloping the sound source, described in ISO 3744 (6), ISO 3745 and ISO 3746.

The second approach to determine the sound power is based on the direct determination of the normal component of the sound intensity which requires the measurement of both the sound pressure and the sound velocity. Whereas the sound pressure measurement is straightforward the sound velocity needs in practice to be calculated by using the pressure gradient defined in one of the basic equations on the acoustic field in fact the one based on Newton´s law of equilibrium. This is

$$\rho \frac{\partial \vec{v}}{\partial t} = -\text{grad } p \tag{6}$$

leading to the following equation with the velocity showing in n-direction

$$v_n \approx -\frac{1}{\rho} \int \frac{\Delta p}{\Delta n} dt \quad . \tag{7}$$

The difference quotient is usually approximated by the difference of the sound pressures measured with the help of two microphones mounted face to face at a distance Δn. Assuring the adequate orientation of this so called intensity probe the sound velocity and finally the sound intensity showing in the direction n can be determined.

However, there are two problems with this approximation of the sound velocity of the pressure gradient. The first one is linked to the electronic phase difference between the two measurement channels in the analyzer which interacts with the phase difference due to the passing sound wave. The second one is related to the distance between the two microphones which needs to be large enough for the lower frequencies in order to get enough phase dynamics but small enough for the higher frequencies in order to avoid subsampling problems. In order to get a sufficiently broad frequency range intensity measurements were carried out with a 12mm or a 8.5 mm spacer.

2.3 Measurements

2.3.1 Sound power level determination applying sound pressure level measurements

The sound power level of a reference sound source type B&K 4204 was measured under repeatability conditions in the anechoic chamber. This means that the measurements were repeated three times by the same staff on 5 successive days including repositioning of the microphones and the RSS at always the same position in the measurement room. The 20 microphone positions were located on a hemispherical enveloping surface representing equal areas on the hemisphere with a radius of 2m. The measurement positions were those specified in Annex B of EN ISO 3744:2010 clause B.2 table B.2 for broadband sources and the sound power was measured as 1/3 octave band spectrum in dB.

To assure a low random error for the broad band noise the observation time T for the lowest 1/3 octave band mid frequency of 50 Hz was calculated from the BT-product relation for a standard deviation of 0.1 dB resulting in a measurement time of 180 s. Figure 4 shows the determined sound power level spectra.

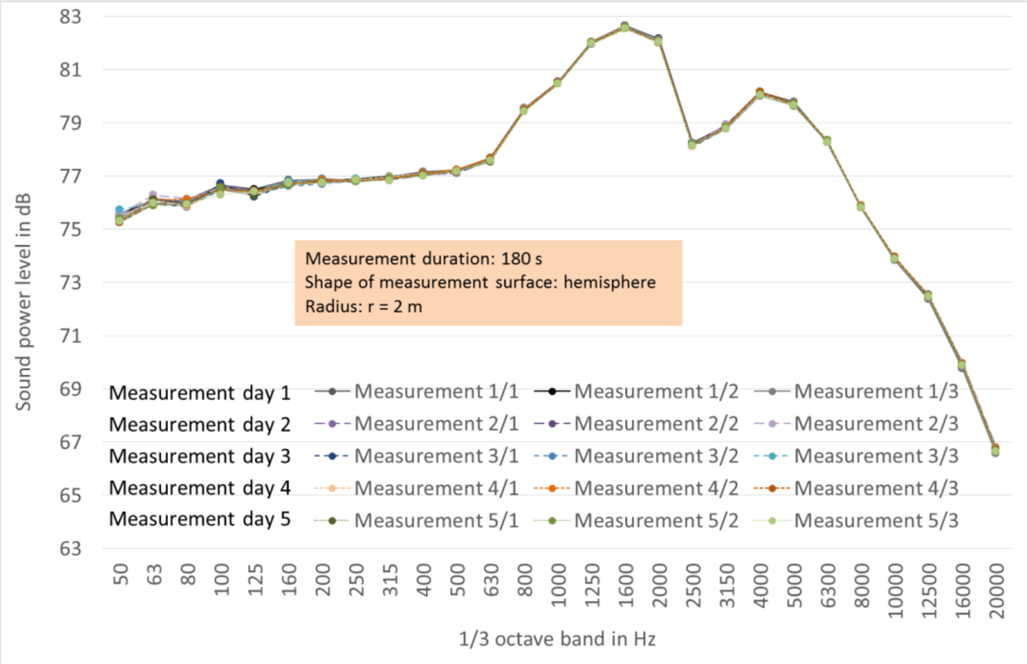

Figure 4 Spectra of in total 15 sound power level measurements of a RSS determined from sound pressure levels at 20 microphone positions on a hemispherical measurement surface

From figure 4 two important findings can be derived

- sound power determinations of a B&K 4204 RSS under free field conditions using the sound pressure level measurement approach will, under repeatability conditions, very likely result in negligible variations of the measurement results and
- the sound generation of the B&K 4204 RSS is nearly constant.

A calculation of the standard deviation resulted in values only slightly exceeding 0.1 dB for 1/3 octave band mid frequencies below 100 Hz. For the machinery noise relevant frequency range of 250 to 10 kHz the standard deviation is less or equal to 0.05 dB in the 1/3 octave bands. Thus, assuming an ideal constant sound source the repeatability of a sound power measurement is extremely high.

2.3.2 Sound power level determination applying sound pressure measurements on enveloping surfaces of different radii

In order to check the influence of the radius of the half sphere enveloping surface on the determined sound power level the radius was varied in steps of 1m from 1 to 4m. The measurement positions were adequately adapted to the increasing radii.
Figure 5 shows a significant difference at lower frequencies between the sound power level spectra of the 1m measurements compared to those made at larger distances. Whereas the measured 1/3 octave band values fit more or less well within the tolerance band given in the calibration certificate of the RSS an obvious deviation occurs in the frequency range between 2000 and 4000 Hz. This has already been noticed when measuring the sound power level spectra of several other RSS in other environments with other measurement arrangements (staff, instrumentation, measurement surface etc.). It seems to be related to the chosen B.2 measurement position arrangement given in ISO 3744 which is not equally distributing the microphone positions on the hemisphere (only 4 heights).
In order to check whether the spectral differences at lower frequencies are caused by airflow, generated by the B&K RSS at closer distances, windshields were attached to the microphones and frequency corrections applied. Obviously the spectra do not significantly change their shape as can be seen from figure 6. For verification purposes the measurements were additionally repeated by using a hand-held sound pressure level meter of class 1 which led to almost identical results.
As the local angle error can be neglected due to the used hemispherical measurement surface, angle α (see equation 2) is almost 0 assuming the RSS to represent a point source at the center point of the half sphere, the local impedance error at a microphone position i should be considered to be the reason for these low frequency differencies including possible deficiences from the free field room assumption.

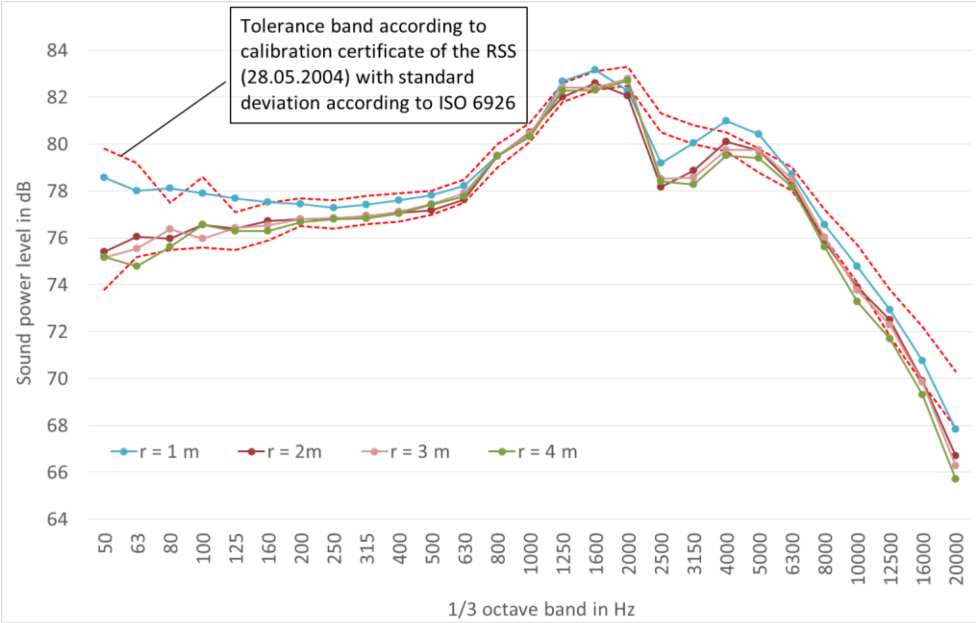

Figure 5 Averaged spectra of sound power level measurements of a B&K reference sound source (RSS) determined from sound pressure level measurements at 20 microphone positions on a hemispherical measurement surface with different radii. The averaged spectra result from 15 measurements each for the 2m and 4m radius, from 8 measurements for the 3m radius and 10 measurements at a radius of 1m

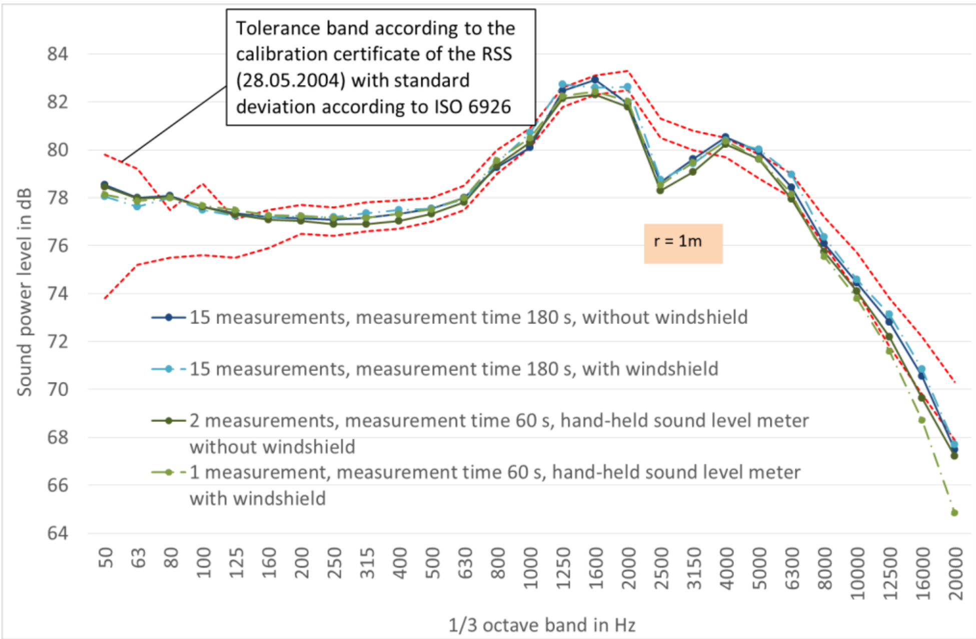

Figure 6 Spectra of the sound power level of a B&K reference sound source (RSS) determined from sound pressure level measurements at 20 microphone positions on a hemispherical measurement surface with a radius of 1m by applying a multi-channel real time measurement equipment or a hand-held sound pressure level meter of class 1 with windshields attached or not attached to the microphones. The windshield influence was corrected as recommended by B&K.

2.3.3 Sound power level determination applying sound intensity measurements on a half sphere enveloping surface

Sound power level spectra of the B&K 4204 RSS were determined by the direct measurement of the normal component of the sound intensity at the same discrete 20 measurement positions on the half sphere enveloping measurement surface as used for the sound pressure approach. The measurement surface had a radius of 3m and the measurements were repeated for three times. Again, the resulting repeatability is very good (see figure 7). For most of the octave bands the standard deviation was less or equal to 0.1 dB with slightly higher values up to 0.14 dB for the lower and higher octave bands. This of course was expected. However, in the frequency range from 2.5 kHz to 5 kHz a prominent increase up to 0.2 dB was noticed. Again, the unequal distribution of the measurement positions seems to be cause.

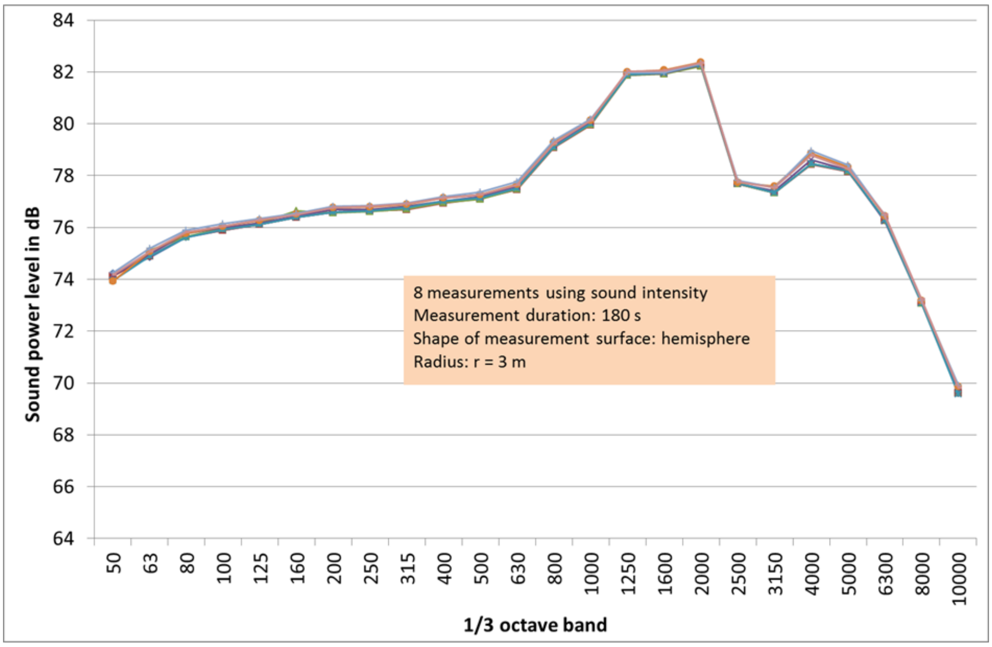

Figure 7 Spectra of 8 sound power level measurements of a B&K 4204 reference sound source (RSS) determined from the normal component of the sound intensity at 20 microphone positions on a hemispherical measurement surface

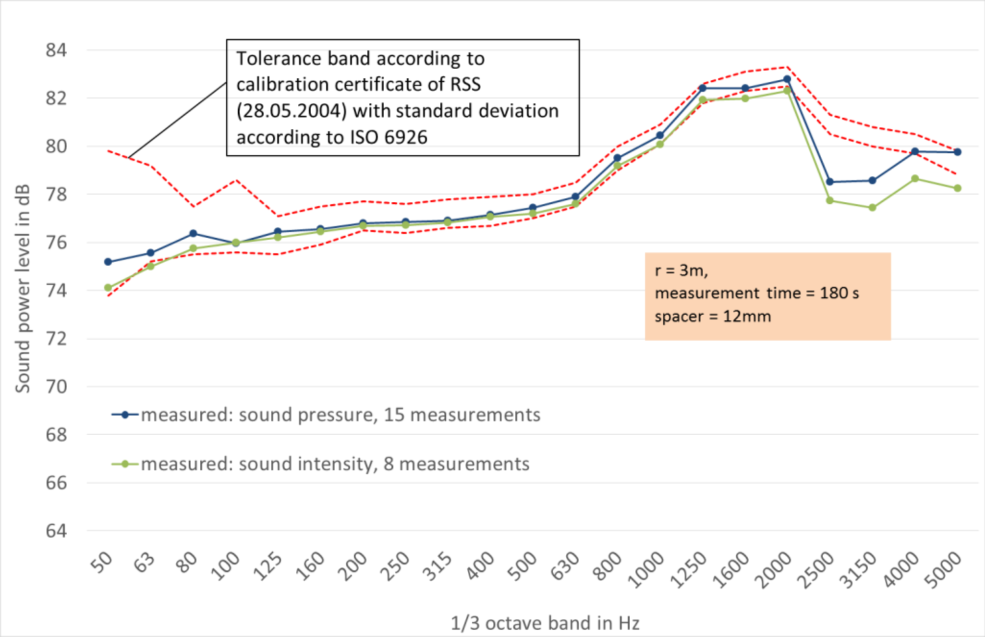

Figure 8 Comparison of the averaged determined sound power level spectra of a B&K reference sound source (RSS) determined from sound pressure and sound intensity measurements at 20 microphone positions on a hemispherical measurement surface with a radius of 3m.

As the sound power was determined from sound pressure in the previous chapter it is interesting to compare the results with those gained by the sound intensity approach. Figure 8 shows a good correspondence of the averaged frequency spectra of the sound power level determined at the 20 microphone positions on a hemisphere with a radius of 3m for the sound pressure and the sound intensity approach. Only at the lower and higher 1/3 octave frequency bands the differences get higher as expected due to the difference approach used to determine sound intensity. In the frequency range considered the differences are less than 1 dB!

2.3.4 Sound power level determination applying sound intensity and sound pressure scanning

The next investigation concentrated on the determination of the sound power level of the RSS type B&K 4204 by applying the scanning method both for sound pressure and sound intensity. The measurements were carried through in the anechoic measurement room using a parallelepiped measurement surface as shown in figure 9. The measurements were performed at least 5 times by the same staff including repeated scanning of each part of the enveloping area. The scanning was done on partial surfaces subdivided in segments of the enveloping surface as required according to ISO 9614-2 respectively -3 (7). The parallelepiped dimensions result from choosing a 1m distance from the reference cube which closely surrounds the RSS which was always placed at the same position in the measurement room.

The sound power level spectra were measured at the same time by scanning both the sound intensity normal to each partial surface of the parallelepiped enveloping surface and the sound pressure. Although the requirements stated in the ISO 9614-2 and -3 apply only for sound intensity they were observed if relevant also for sound pressure. At least the scanning paths and the scanning times were identical.

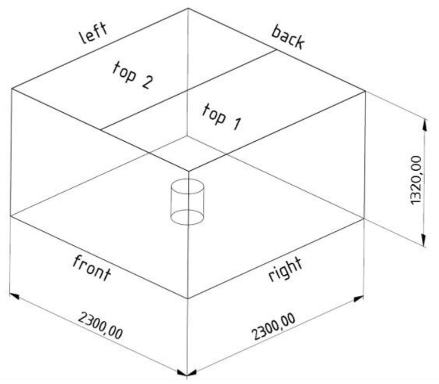

Figure 9 Dimensions of the applied parallelepiped measurement surface including the equal division of the top area

Concerning the grade 1 requirements in ISO 9614-3 the partial surfaces of the side faces were subdivided in segments according to clause 8.2 of the standard with a division of the top face into two sub areas each consisting of 18 segments. Generally all requirements stated in the two ISO standards on scanning were carefully observed. This includes the so called field criteria in order to achieve the desired accuracy. Hence,

criteria 1 dealing with the repeatability of the scan on a partial surface, criteria 2 checking the adequacy of the measurement equipment, criteria 3 checking the presence of relevant extraneous noise and criteria 4 the check for the field non-uniformity were accomplished.

Considering criteria 1

$$\left|\bar{L}_{I_{n(1)}} - \bar{L}_{I_{n(2)}}\right| \leq \frac{s}{2} \tag{13}$$

the results showed significant lower values compared to the required s/2 (s=standard deviation of reproducibility) according to Table 1 of ISO 9614-3. However, there were some exceptions at the very low end of the 1/3 octave band spectra (mostly below the 160 Hz band) where occasionally but not systematically significant higher values were detected for all partial surfaces when repeating the measurements.

Criteria 2 to 4 were satisfied with some exceptions for the criteria 4 at the lower 1/3 octave band frequencies.

As a kind of global result figure 6 shows the sound power level spectra gained from scanning the normal sound intensity on the parallelepiped following the requirements of the grade 1 measurement method specified in ISO 9614-3 and grade 2 according to ISO 9614-2 in comparison with a respective sound pressure scan on the same surface observing adequately the same criteria if relevant and using two different spacers. The sound pressure was that directly provided at the output of the B&K “Pulse” analyzer.

The rounded total sound power level L_{Wtotal} shows a difference between those gained from sound pressure and those gained from sound intensity measurements of about 1 dB. The sound pressure related results show a very low spread of values for almost all 1/3 octave frequency bands.
The sound intensity measurements show a slightly higher sound power at the lower frequencies for the 8,5 mm spacer.

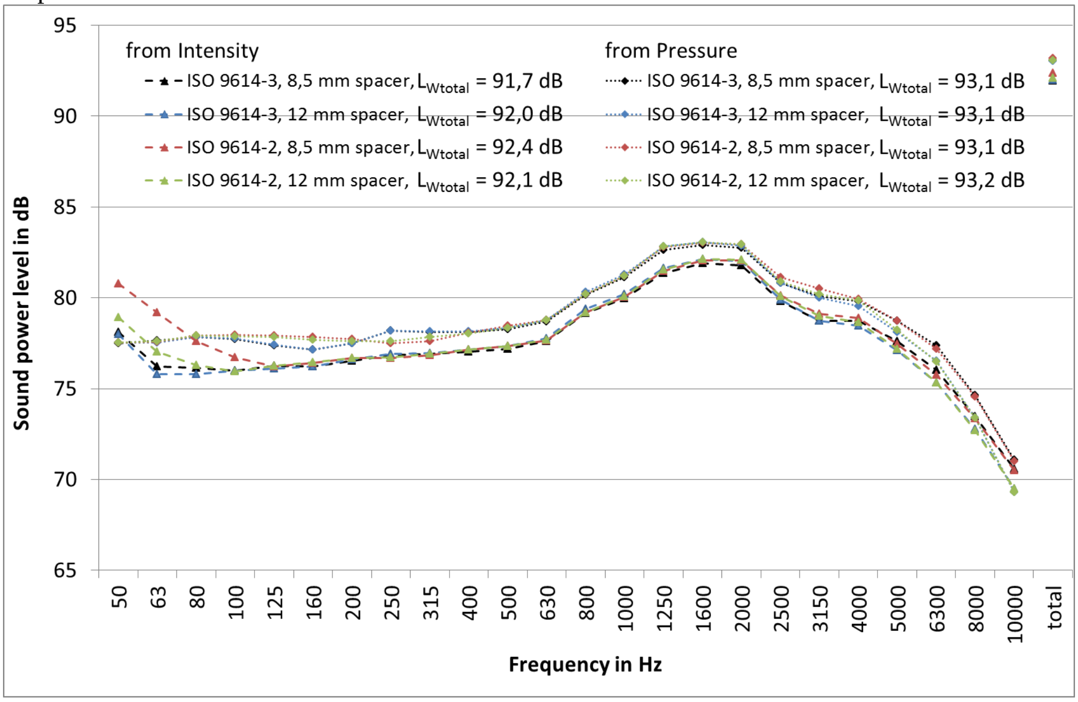

Figure 7 Mean 1/3 octave band sound power level spectra determined from scanning measurements using sound pressure respectively sound intensity, with the latter performed according to ISO 9614-3 respectively ISO 9614-2 applying a 8,5 mm respectively a 12 mm spacer on a parallelepiped measurement surface. The sound pressure used was that directly provided by the analyzer.

Figure 8 allows a quick comparison of the sound power level spectra determined from sound intensity and sound pressure as the respective differences are plotted over the frequency bands. As expected, differences increase at higher or at lower frequency bands depending on the applied spacer. At higher frequencies the sound power is underestimated for the 12 mm spacer which is an expected result. Significant differences in applying a grade 1 or grade 2 measurement method cannot be detected. For the very low frequency bands however, the results give cause to reflect because the values especially for the 8,5 mm spacer measured according ISO 9614-2 are not in line with the expectations. A comparison with figure 7 gives the impression that the room cannot any more be interpreted as a free field room at these low frequencies.

3. CONCLUSIONS

The measurement results allow making the following statements:

- Repeatability of sound power measurements in an essentially free field using sound pressure and sound intensity on a stable source is extremely good (the standard deviation is less or equal to 0.1 dB in the 1/3 octave bands for a frequency range from 100 Hz to 10 kHz)
- The measurement of the sound power level of the RSS applying sound intensity scanning according to ISO 9614-2, -3 respectively sound pressure scanning on a parallelepiped enveloping surface, shows a very good repeatability with standard deviations below 0,25 dB for the frequency range between 100 Hz to 10 kHz and a difference of the sound power level about 1 dB in the machinery noise relevant frequency range.
- Assuming free field conditions no relevant differences can be expected between sound power measurements of an RSS using the grade 1 or grade 2 measurement procedures describing sound intensity scanning.
- The practical application of the grade 1 sound intensity scanning method showed clearly that

this method was primarily drafted for using automated scanning devices. The scanning by hand requires in practice too much effort and seems to be almost impossible if the partial surfaces to be scanned in segments get too large due to the dimensions of the sound source!

- The sound power level spectrum of the RSS shows a rise in the frequency range between 1000 and 2500 Hz, with a greater significance if a half sphere is used instead of the parallelepiped measurement surface.

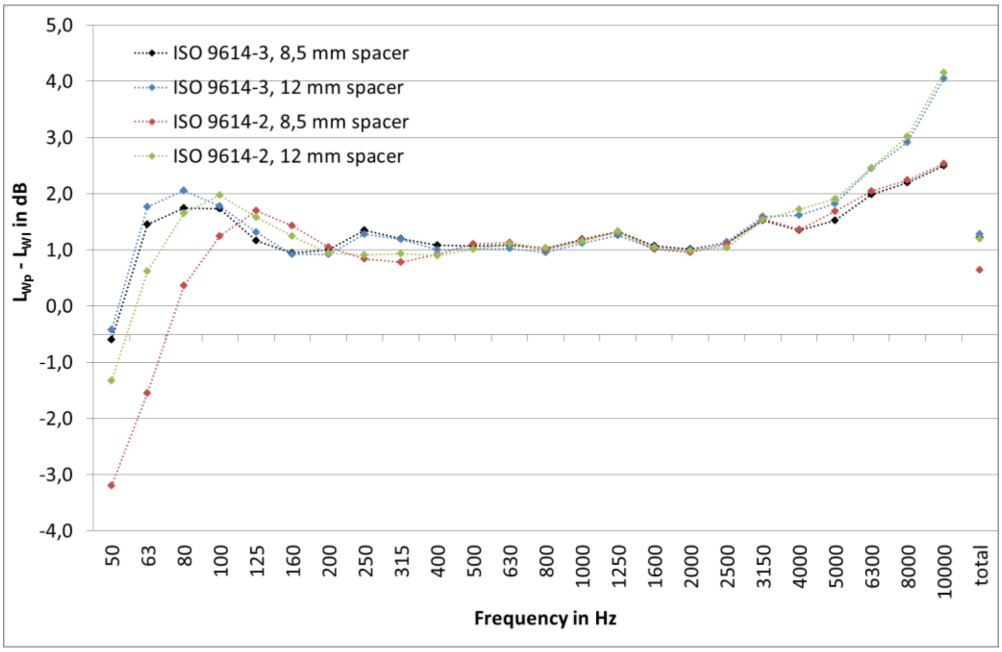

Figure 8 Mean differences of the sound power of the RSS determined from sound pressure respectively sound intensity scanning measurements in 1/3 octave bands according to ISO 9614-2 or -3 using two different spacers.

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