SERT – The Calculation of Sound Propagation in Workrooms

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Introduction

Since the 1970s some proposals for the calculation of sound propagation in the frame of noise prediction for workrooms with machinery have been published (e.g. /1/ - /7/). The final method to be applied in all cases with legal requirements and to be standardized as guideline VDI 3760 was selected in a joint project /8/ financed by the German BAU (Bundesanstalt für Arbeitsschutz) that was later extended by more than 100 measurements in industrial halls with machinery. With this method the sound field in a room is determined applying the mirror image technique including a statistical approach about sound scattering according to Kuttruff and Jovicic. This method showed the smallest deviation between calculated and measured sound pressure levels in comparison with 8 other methods – it was standardized as guideline VDI 3760 /10/. In a later investigation /11/ the possible extension of this method including screening structures, large machines that cannot be simulated by a simple point source and coupled rooms was developed.

Guideline VDI 3760 is still the only validated and – in Germany - standardized method to be used for the acoustic description of workrooms with noise relevant machinery and workplaces. Although many proposals and studies about calculation of sound propagation in rooms mainly with the target of a good speech understandability and music performance have been developed and published no further step was made to adapt VDI 3760 to the new and by far advanced computer and software techniques. This is the target of this paper – the described SERT method (SERT – Stochastic Energy Ray Tracing) is proposed to replace the method VDI 3760 and to be applied in all cases where sound pressure levels, reverberation times and all other values based on them shall be predicted.

As starting point the most important features and properties of the calculation method VDI 3760 are shortly summarized.

- Sound is exclusively regarded as a flow of energy – sources are described by sound power levels and the sound pressure levels are determined from sound energy densities. Incoherent superposition of different sound contributions is assumed if the resulting level of more contributions is determined. A simplified mirror image method is applied - even the contributions of direct sound and different reflections from one and the same source are summed up purely energetically. This method is similar to the calculation of sound outside with ISO 9613-2 /12/. But it is one of the shortcomings of the method that diffuse reflection at structured surfaces or surfaces uneven due to many technical installations typical for industrial environments cannot be taken into account.
- The method can only be applied with box shaped rooms with 6 surfaces in parallel and right-angled arrangement – this was necessary to get acceptable calculation times due to the state of computer technique when VDI 3760 was developed. All other shapes of rooms had to be approximated by a box.
- Each of these 6 surfaces of a room is acoustically characterized by a mean absoption spectrum for the octave bands from 125 Hz up to 4000 Hz. This not very detailed and rough description was sufficient because the calculation of the localized reflection point of each ray

to take into account the locally given absorption was not possible due to acceptable calculation time. Even if it is possible to define differently absorbing parts of such a room surface only the average for the complete surface was taken into account for the calculation. It is a clear disadvantage of the method that therefore only locally effective measures like the treatment of a wall-surface behind a noisy machine with an absorbing plate cannot be taken into account correctly.

- Machines and other acoustically opaque objects are taken into account by a mean scattering density relevant for the whole room – the locally different effect of screening and reflecting objects cannot be described and evaluated with this method.
- With VDI 3760 it is assumed that the sound pressure level caused by a point source without directivity depends only on the sound power level of the source and on the distance source – receiver. The spatial sound decay on straight paths starting at the source is independent from the location and direction of the path.
- Due to this simplification spatial sound decay has only to be calculated once for a room. With more than one sound sources the different contributions of them are determined applying this room-specific decay curve SDC and are summed up energetically.

The method of VDI 3760 is still valid and sufficient to calculate the mean sound propagation in a workroom, to qualify its acoustic properties by a mean sound decay curve SDC or by the characteristic values DL2 (level decrease by doubling the distance) and DLf (level difference to free field) and in simple cases even to calculate expected sound pressure levels with given sources, if the distribution of the absorption on surfaces and of reflecting and screening objects can be regarded to be the same in all subparts.

In the following an advanced calculation method is presented that has been developed to follow up and replace the method of VDI 3760, but keeps the approved method of a pure energetic superposition different sound contributions to determine the sound impact at work places from the emission of technical sound sources like machinery. Most effort is invested in the detailed description of the often very complex sound sources and propagation conditions, but all phase related aspects that are generally not relevant in such industrial environments are still neglected. Most of the shortcomings of VDI 3760 mentioned above are avoided applying existing computer technology to improve the accuracy of noise predictions. The method was validated by comparison of measured and calculated sound pressure levels on paths in 122 rooms – see below – and by the determination of the absorption of baffle-systems in a „virtual“ reverberation chamber /13/. It is an eligibly method to determine the sound pressure levels at work places in production halls from the sound emission values according to the European machine directive.

General Description of an Energy-based Particle Method SERT

The radiation of particles by a sound source

Different to the mirror image method according to VDI 3760 with the energy based particle method (SERT - Stochastic Energetic Ray Tracing) described in this paper the possible ray paths from a source to a receiver are not calculated strong deterministic. As it is shown in figure 1 with a point source in the middle of a room, the source radiates sound particles into statistically distributed and randomly selected directions, where the probability for all angles is the same. Their path is calculated up to a distance depending on the propagation time needed for the specific task or for a required accuracy.

With increasing particle number the particle density gets identical for all elements of the solid angle around the source.

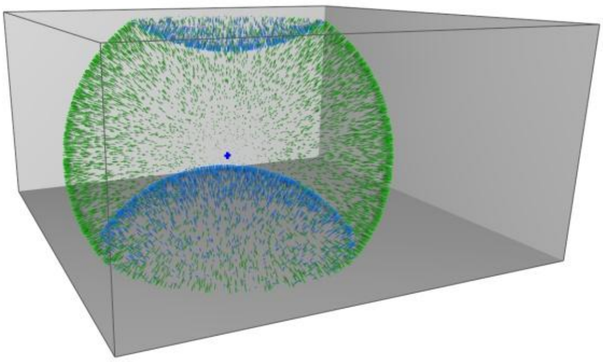

Figure 1: Visualisation of the particles radiated at the same time from a point source after the first reflection at the floor and the ceiling. In this example the colour shows the number of reflections having occurred (0 order or direct sound green, 1st order blue)

The Determination of Energy-Densities and Sound-Pressure Levels

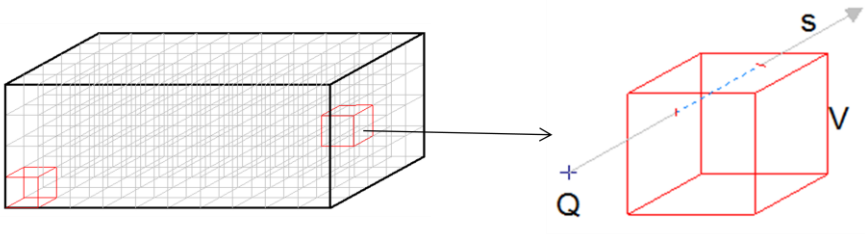

Figure 2: Subdivision of the relevant room volume in voxels

As shown in figure 2, the room volume is subdivided in smaller counting volume elements – the voxels – and for each of these voxels the stationary energy density is determined from the number of particles crossing it. Depending on the selected strategy cubic or spheric voxels can be applied. The size of the voxels determines the acoustic resolution of the model for the final level distribution.

With a sound power level L_W of the source and N particles radiated, the sound power transferred by one particle is

$$I_{W,T} = \frac{10^{0,1 \cdot L_W}}{N} \qquad (1)$$

With voxels not spherical a weighting of the energy contribution according to crossing length x inside the voxel is necessary to eliminate the dependency of the cross-section in path direction from its orientation in the room. With the crossing length x and the Volume V of the voxel the relevant cross section is

$$S = \frac{V}{x} \qquad (2)$$

and the contribution to the intensity is

$$I_T = \frac{x \cdot 10^{0,1 \cdot L_W}}{N \cdot V} \qquad (3)$$

With the absorptions α_i cumulated along the propagation path

$$\left(1 - \alpha_{eff}\right) = \prod(1 - \alpha_i) \qquad (4)$$

and the absorption of air $\propto_L$ in dB/m the remaining sound intensity is

$$I_T = \frac{x \cdot 10^{0,1 \cdot L_W}}{N \cdot V} \cdot 10^{-0,1 \cdot d \cdot \alpha_L} \cdot \prod(1 - \alpha_i) \qquad (5)$$

All relevant contributions are summed up for all sources and all ray paths in each voxel and the final sound pressure level can be determined from

$$L = 10 \cdot \log\left(\sum I_T\right) \qquad (6)$$

Similar to VDI 3760 this calculation is performed for octave bands – for example from 125 Hz up to 8000 Hz.

Sound Radiation with Directivity

If a sound source radiates with directivity – the intensity is not independent from the direction – this can be simulated with a still direction-independent density of particles, but with a particle energy modeling this directivity. Or the particle energy is still in accordance with equation (1) and the probability to be radiated in a certain direction is determined by the directivity.

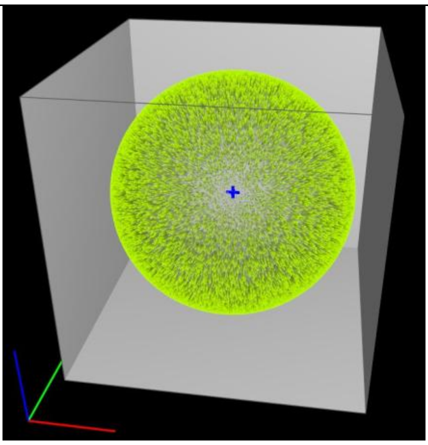

Figure 3: Directivity determines the particle energy

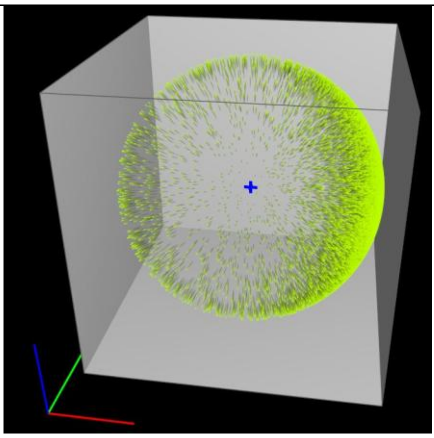

Figure 4: Directivity determines the angular distribution

Extended sources like line- or area-sources are subdivided in elements small enough that they can be replaced by point sources. The description above is therefore true for all these source types.

Acoustic Properties of Objects – Modeling of Complex Sources

Each object to model the room and the technical facilities inside is defined acoustically by three parameters in each frequency band – the absorption coefficient α, the transmission index τ and the index for scattering s (to determine the ratio of diffuse and specular reflected energy).

Figure 5 shows the relations between the two first parameters for a plate. A part τ of the sound energy E incident from the left side is transmitted to the right side, and taking into account an absorption coefficient α the part (1 – τ – α) is reflected back.

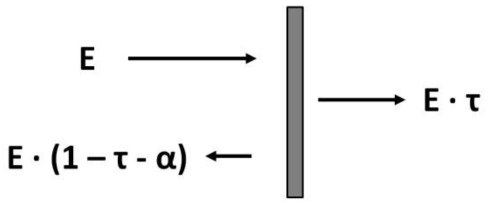

Figure 5: Transmission, absorption und reflection with a plate

The index for scattering s defining the ratio of diffusely reflected to all reflected energy will influence the direction of the ray reflected to the left in figure 5.

With these elements of sources and structures even complex sources like machinery or other technical facilities can be modeled. Figure 6 shows an example with a 4-station printing machine.

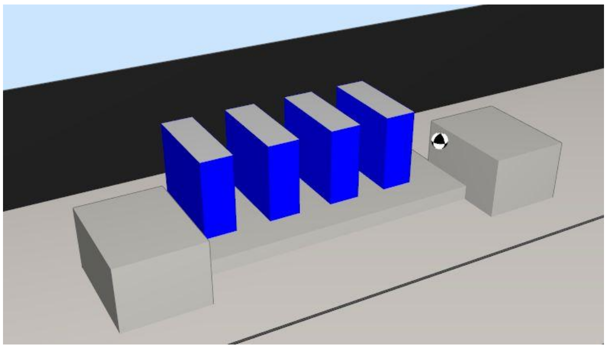

Figure 6: Acoustic model of a 4-station printing machine (radiating area-sources are blue)

To calculate the sound pressure levels at defined receiver positions these are interpolated from the values determined at the voxels around.

The Energetic Echogram and the Decay-Curve to determine the Reverberation Time

For each voxel the energy contribution of each particle crossing it and its corresponding propagation time is known. These energy contributions can therefore be dedicated to a time axis and an energy related impulse response or echogram (lower curve figure 7) can be derived. The decay curve measurable if a source is switched off is derived from this echogram by backward integration (upper curve figure 7) and from this decay curve the reverberation time and many room acoustic parameters based on it are calculated.

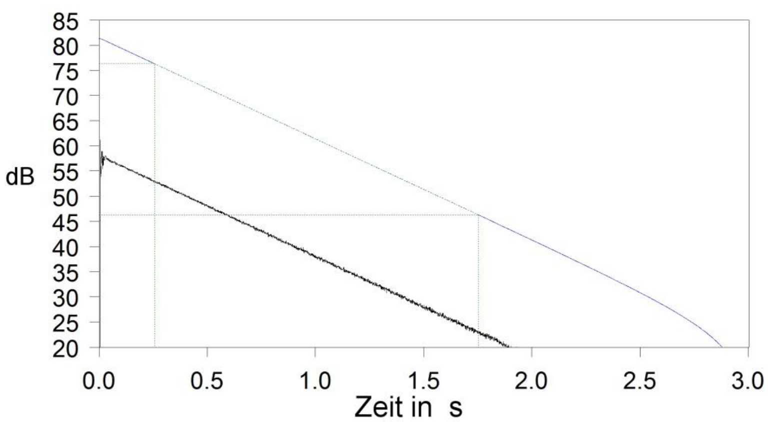

Figure 7: The echogram (lower curve) and the energy decay (upper curve) to determine the reverberation time.

Diffraction and Screening

The calculation of sound pressure levels due to diffracted sound behind acoustically opaque structures is a problem only approximately solved with the described particle methodology. In cases where multiple reflected sound from the room and other surfaces gets weak due to large dimensions of the room or high absorption at the surfaces there is a continuous transition to free-field above reflecting plane – in such cases the sound pressure level behind partial walls and other objects may be determined by diffraction and the final accuracy of predictions may be determined by the strategy applied.

One method is to calculate diffraction only for the direct sound and to apply the well proven Maekawa-equations only for the rays source – receiver as it is well experienced with sound propagation calculations outside. The screening objects between source Q and receiver E are cut by two planes containing S and E and vertical to one another, where one plane is vertical to the horizontal ground plane. In these two planes the shortest path Q→E and the shortest possible additional path-length z relative to the direct connection QE is determined.

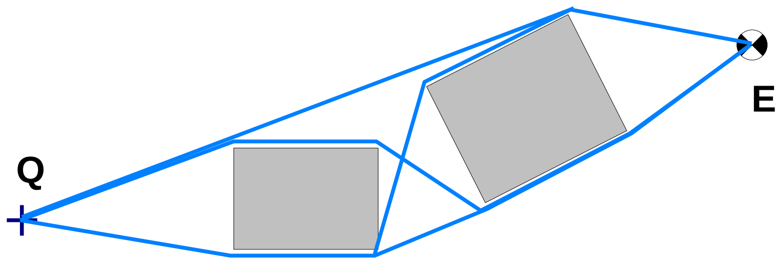

Figure 8: The 4 possible paths in one plane with two objects between Q and E

The decrease of the sound pressure level calculated without screening objects D_z for a given additional path-length z in a frequency band with a wavelength λ is

$$D_z = 10lg\left(3 + \frac{40z}{\lambda}\right) \text{ dB} \qquad (7)$$

Many approaches have been made to replace this concept based on an attenuation of the direct sound by techniques directly integrated in the particle concept. One method is to deflect each particle crossing above a bending edge in a way that the equation (7) is reproduced in cases where it has been proven to be valid.

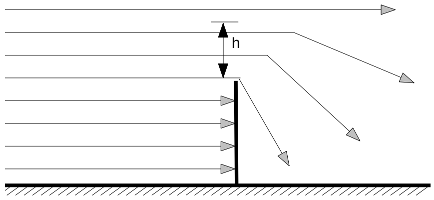

Figure 9: Deflection of particles crossing a gap of width h above the bending edge.

But a general solution applicable in all possible combinations of bending edges and particle paths needs a lot of verification effort - this work is still in progress and is not finalized till now.

Validation of the SERT-Method

Comparison measurement – calculation with 122 industrial halls

Strategy

To investigate the finally resulting accuracy and thus to validate the SERT-method it was possible to use data that have been cumulated during the development of VDI 3760 with financial support of the BAuA (Federal Institute for Occupational Safety and Health). The task was and is to recalculate the sound pressure levels at all receiver positions along a straight path starting at the source position for all halls where measurements have been made and to evaluate the differences calculated – measured sound pressure level. This allows to rank the uncertainty of a method for the calculation of sound propagation on a statistically secured basis.

Input data

The measurements were carried out continuously during about 10 years in plants and industrial areas - figure 10 shows as an example the measurement setup in a bottling plant.

Figure 10: The dodecahedron loudspeaker as sound source to measure sound propagation along a path in a bottling plant

Figure 11 is a set of data with all geometric and acoustic parameters of room, source and receivers as well as the measured octave band spectra measured at all receiver positions. Machinery and other installations are taken into account by the parameter "fitting density".

1	3						ObjektNr / ZustandsNr		
Industriebetrieb XXYZ							Name		
mit RA-Massnahmen / mit Maschinen							Zustand		
30	20	4.5					Länge / Breite / Höhe		
0.045							Streukörperdichte		
0.06	0.075	0.075	0.075	0.085	0.105		Streukörperabsorption		
0.06	0.073	0.074	0.076	0.08	0.1		Absorptionsgrad Wand 1		
0.06	0.073	0.074	0.076	0.08	0.1		Absorptionsgrad Wand 2		
0.06	0.073	0.074	0.076	0.08	0.1		Absorptionsgrad Wand 3		
0.06	0.073	0.074	0.076	0.08	0.1		Absorptionsgrad Wand 4		
0.25	0.5	0.65	0.8	0.85	0.85		Absorptionsgrad Decke		
0.06	0.073	0.074	0.076	0.08	0.1		Absorptionsgrad Boden		
1	0.88	0.72	0.65	0.64	0.58		Nachhallzeiten		
107.9	112.8	108.6	104.4	104.6	97.7		Schalleistungspegel Quelle		
1.5	9	1.5	30	9	1.5		Pfadanfang X/Y/Z, Pfadende X/Y/Z		
1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10 / 12 / 14 / 16 / 18 / 20 / 22 /							Abstände Quelle - IP		
100.0	101.7	97.9	95.5	94.8	89.7		IP 1		
94.1	98.9	94.5	91.5	92.3	85.0		IP 2		
92.3	94.3	89.9	87.2	86.7	80.8		IP 3		
91.3	92.1	88.9	87.4	85.5	78.9		IP 4		
91.1	91.3	88.2	85.5	85.7	78.9		IP 5		
88.8	90.3	87.0	84.0	86.7	78.2		IP 6		
87.0	89.9	85.7	83.1	85.5	78.1		IP 7		
88.5	89.5	85.2	82.7	84.3	77.9		IP 8		
89.4	89.0	85.7	81.4	84.4	76.7		IP 9		
91.8	89.3	83.1	80.8	82.7	75.1		IP 10		
86.9	89.2	82.6	78.8	81.4	73.9		IP 11		
83.7	86.2	80.6	75.5	79.0	72.3		IP 12		
87.2	86.7	79.7	75.0	77.6	70.6		IP 13		
85.4	86.6	78.4	73.6	76.8	69.4		IP 14		
85.0	84.8	78.0	73.7	76.3	68.6		IP 15		
84.6	85.2	76.5	73.8	76.2	68.9		IP 16		

Figure 11: Set of data describing geometry and acoustic properties of a room and the measured values

The frequency dependent absorption coefficients of the 6 room surfaces have been derived from measurements of the reverberation time in 10 empty industrial halls as starting point of the project.

The fitting density was estimated dividing the room volume by 4 times the surface of all objects in the room according to equation (7) in VDI 3760. Taking into account the uneven distribution of scattering objects in such environments it is clear that such a single number description cannot be very accurate.

Having 122 datasets of the type shown in figure 11 a procedure was developed to generate 3-dimensional models of these halls with their measurement setup with the correct location of the source representing the dodecahedron loudspeaker and the chain of receivers as it is shown in figure 12, to calculate the sound pressure levels at these receivers and to evaluate the differences calculated and measured levels.

Generating these models from the datasets it was necessary to distribute sound reflecting objects according to the known fitting density q to represent the machinery in the room. The distance d of the evenly arranged reflecting cubes was derived in each case from the above mentioned fitting density q.

Figure 12 is an example where the edge length of the cubes representing the reflecting technical installations was 2m.

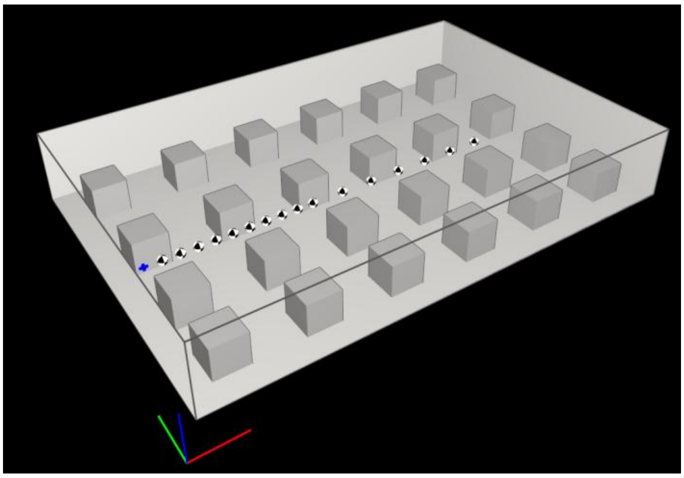

Figure 12: The 3-dimensional model of one of the 122 halls

The surface of the „machine-cubes“ was assumed to reflect sound diffusely with a scattering index 1. Due to this assumption the influence of the detailed arrangement of the objects has only little influence on the sound propagation along the free receiver paths.

In some cases the measurements could be carried out in different conditions of one and the same hall. There are the 4 different conditions empty (1), empty but with absorbing treatment - absorbing baffle system or suspended ceiling in most cases – (2), machinery installed and absorbing treatment (3) and finally no absorbing treatment but machinery installed (4).

Evaluation and Results

With $L_{W,f}$ for sound power level in frequency band f, $L_{meas,f}$ the measured sound pressure level in frequency band f and $L_{calc,f}$ the sound pressure level in frequency band f calculated with the same sound power level of the source the normalized levels $D_{meas,f} = L_{meas,f} - L_{W,f}$ and $D_{calc,f} = L_{calc,f} - L_{W,f}$ are determined.

Generally the uncertainty of the calculation of sound propagation for a typical frequency spectrum of the source sound power level $L^*_{W,f}$ is of interest. This can be evaluated applying the normalized A-weighted sound pressure level D_A that is derived from the normalized levels D_f with equation (9).

$$D_A = \frac{\sum 10^{0,1\cdot(D_f + L^*{W,f})}}{\sum 10^{0,1\cdot L^*{W,f}}} \quad \text{dB} \qquad (9)$$

Figures 13, 14 and 15 show these normalized A-weighted levels ($L^*_{W,f}$ pink source spectrum of sound power level) in dependence of the distance source – receiver for one and the same hall first empty, then after installation of an absorbing baffle system and finally after installation of the bottling plant.

These diagrams show a very good agreement between the sound pressure levels measured and calculated with the SERT method, especially if the rough estimation stratefgy for the acoustic room parameters like scattering density and absorption of the surfaces is taken into account.

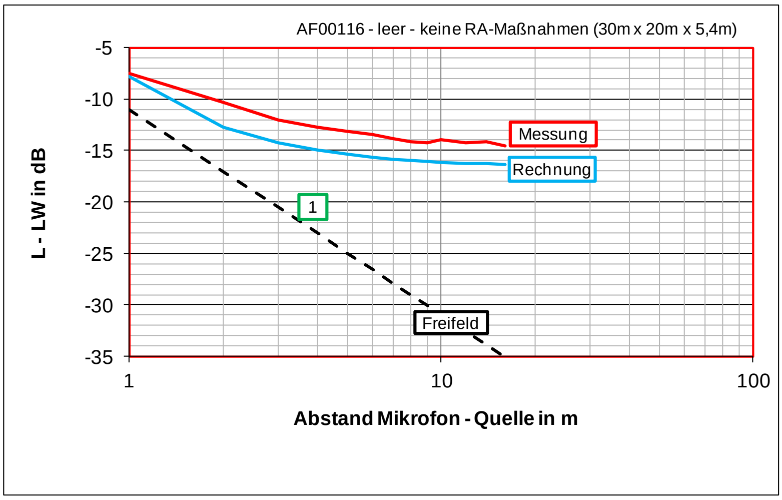

Figure 13: Calculated and measured spatial sound decay curves for a hall in condition 1 (empty, not treated)

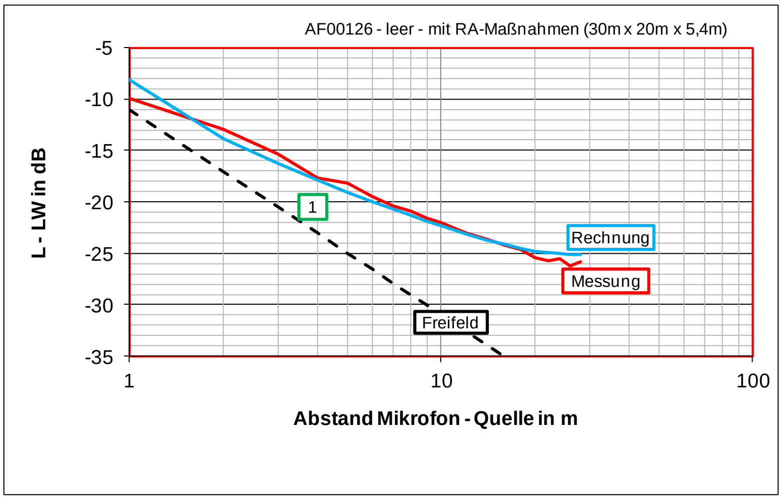

Figure 14: Spatial sound decay curves for the same hall in condition 2 (empty, with absorbing ceiling)

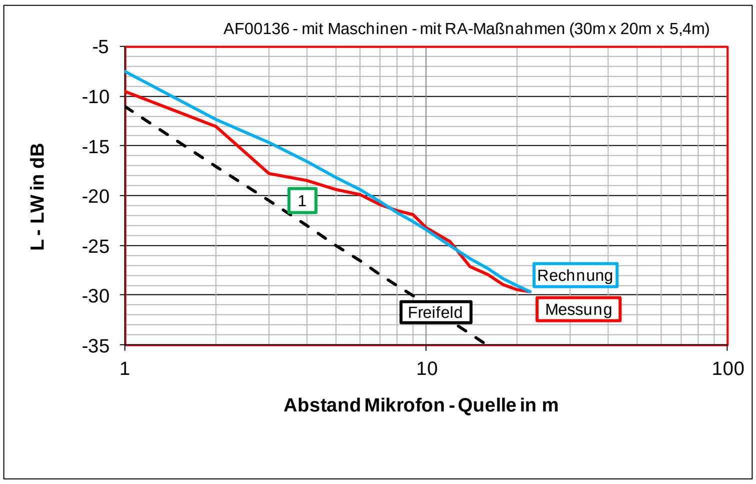

Figure 15: Spatial sound decay curves for the same hall in condition 3 (machinery installed, with absorbing ceiling)

Further mean value and standard deviation were evaluated for the differences $D_{A,calc} - D_{A,meas}$ regarding all 122 halls together and for the 4 conditions separately. In figure 16 the distribution of the spread (mean value ± standard deviation) for the first 5 points up to the distance of 5 m, in figure 17 for the points in distances from 5m to 16m are shown.

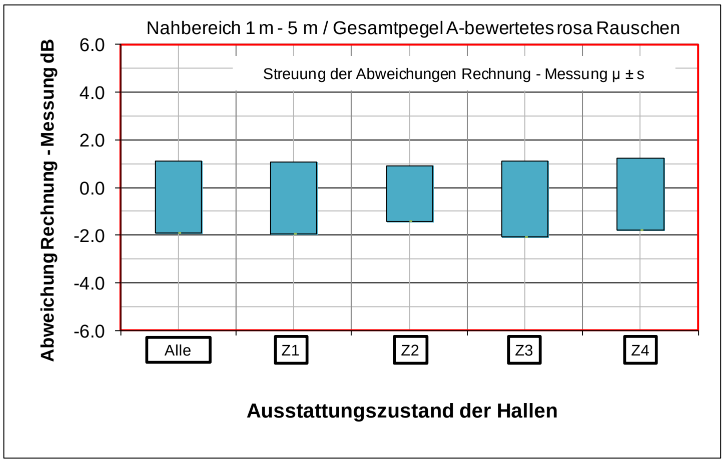

Figure 16: Deviations calculation – measurement – small distance source receiver (1m - 5m)

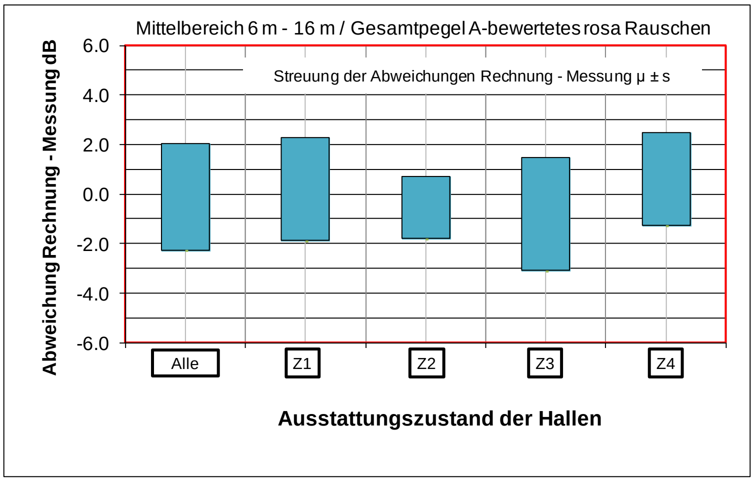

Figure 17: Deviations calculation – measurement – large distance source receiver (5m - 16m)

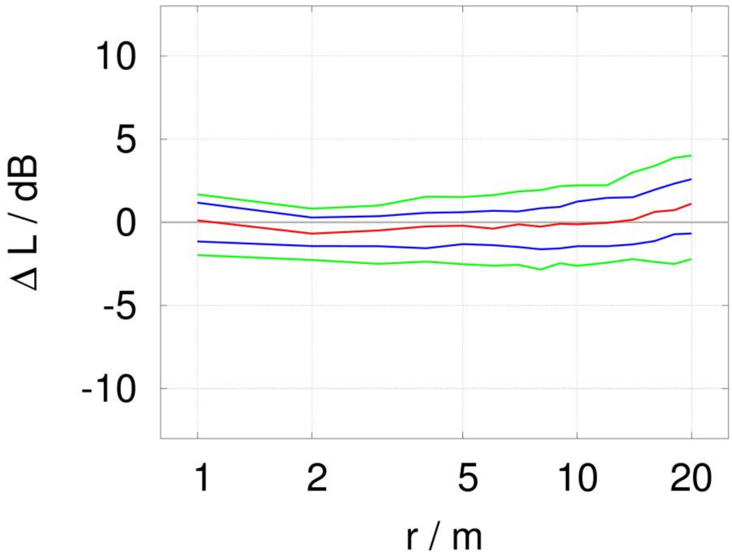

Figure 18: Intervals of the deviation of the A-weighted level – blue lines enclose 50% and green lines enclose 80% of all values

Figure 18 shows the intervals in dependence of the distance not exceeded by 50% (blue) and by 80% (green) of all values calculated – measured sound pressure level. The curve representing the mean value (red) indicates that the systematic deviation does not exceed 1 dB at all distances.

A better agreement cannot be expected for this rather large sample taking into account the above mentioned rough estimation method of acoustic input parameters. Herewith the SERT method is validated with the same procedure as it has been done with VDI 3760. But this is only the description of a „mean“ sound propagation based on the mean values of acoustic parameters like absorption and scattering densities. The SERT method is not submitted the restrictions and shortcomings of VDI 3760 as they were described in the introduction, but opens the field of noise prediction in workrooms to a much more detailed inclusion of not cubic room shapes, complex sources like large machines and a detailed inclusion of the real distribution of absorbing and reflecting objects.

Short Summary – the SERT Method for Noise Prediction and Optimization of Speech Transmission

SERT is a method to calculate the 3-dimensional propagation of sound energy. It can be used with any environment, but due to the equivalent inclusion of all 3 dimensions and the linear influence of reflection order on calculation time it is especially effective with sound propagation in partially or completely enclosed spaces. Neglecting phases and other wave related properties of sound it is the optimal technique for problems where many contributions determine the target values or where these wave related effects are generally not relevant. This is the case in working areas, where the sources are machines or other technical devices or in open plan offices, restaurants or other rooms where people are sources as well as receivers and the sound from different sources is not correlated. Neglecting these phase related aspects the SERT-method allows a very detailed description of sources and environments and is best fitted for noise prediction calculations in working rooms with machinery. It allows further to calculate reverberation time and all acoustic parameters based on the energetic impulse response as it is the case with the Speech Transmission Index STI. The SRT method is the logic successor of VDI 3760 if sound propagation in workrooms or other rooms where people are staying shall be predicted.

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