Determination of the absorption coefficient of structured absorbing systems in a "virtual" reverberation chamber - an application of the sound particle method SERT

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Summary

The following is a case study for an application of acoustic simulation techniques. Starting point was the task to predict the possible noise reduction at the work places in an industrial production hall and the decrease of reverberation time if a planned baffle system would be installed as recommended by the supplier.

After a thorough inspection of the test certificate for the baffle system it was decided that the declared absorption data could not directly be applied in acoustic calculations, e.g. to predict the reverberation time and reduction of noise levels. The measurements performed in the reverberation chamber and especially the measurement setup were not in agreement with the requirements of the cited standard ISO 354 [1] and therefore the declared absorption data would result in an overestimation of the systems acoustic performance. The case is exemplary and therefore the steps to derive the absorption coefficients according to the standard from those measured with any other - but in detail documented - setup are presented as a method generally applicable in such cases. Further some shortcomings of standards concerning the definition of the acoustic properties of absorbing structures are shown up and strategies to solve them are presented.

The basic principles of the simulation technique SERT

The following investigation was based on the application of the simulation technique SERT (Stochastic Energy-based Ray Tracing) implemented in the software package CadnaR [2] - a general overview about particle methods is given in [3].

The 3D-view in figure 1 shows a burst of sound particles radiated from a point source. The path-length of each particle is calculated up to a certain propagation time depending on uncertainty aspects for the target parameters at the receiver positions. The start-direction of each particle-trajectory is determined statistically to realize a uniform distribution in each element of the solid angle.

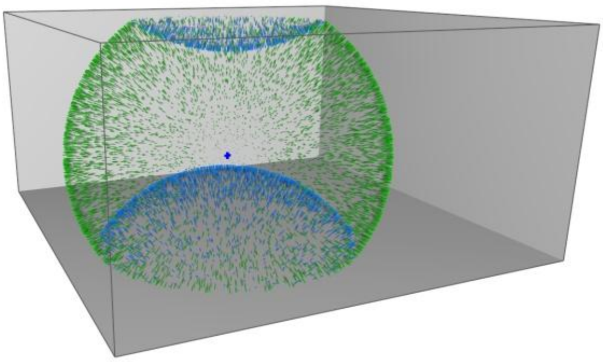

Figure 1: Visualization of the radiated particles after a propagation time where a first order reflection has occurred at the floor and the ceiling. The color is used to show the reflection order (0 order or direct sound green, first order blue)

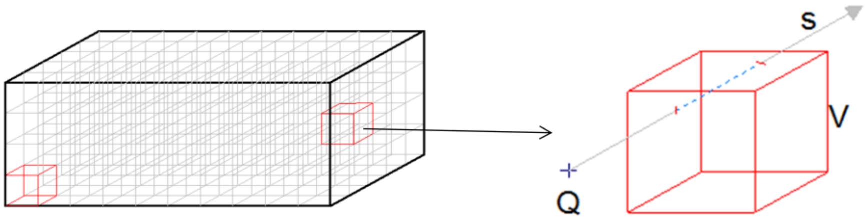

Figure 2: Subdivision of the volume in voxels (volume elements)

Figure 2 shows the sub-partitioning of the room volume in counting volumes (voxels). The number of particles crossing each voxel weighted with the path-length inside is summed up to derive the energy density for the center point. The size of the voxels determines the final resolution for the calculated target parameters.

The sound pressure levels at defined receiver points are interpolated from the values determined at the centers of the voxels around. The sound energy summed up for a voxel can be classified according to the propagation time since radiation from the source and the energy-based impulse response or echogram according to the lower curve in figure 3 can be derived. The decay-curve resulting when the constant radiating source will be switched off (upper curve) is determined by backward integration of this echogram-curve according to [4]. The reverberation time and many other room acoustic parameters can be derived from this decay-curve.

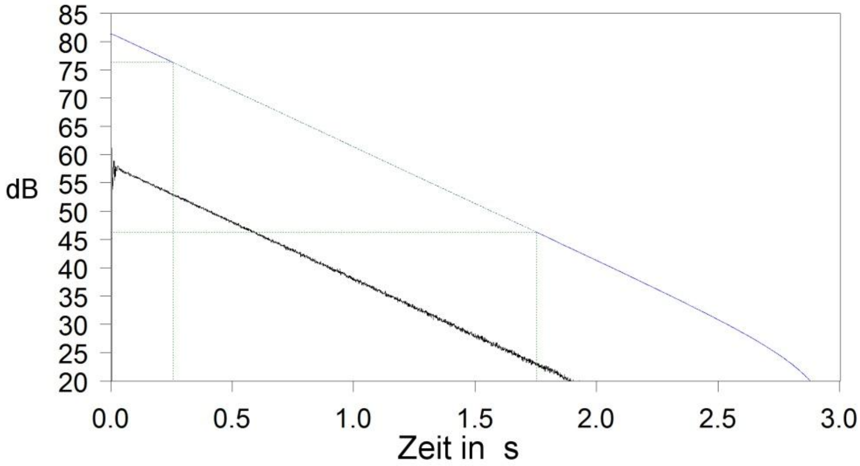

Figure 3: Echogram (lower curve) determined from the particle impact classified according to the propagation time and the decay-curve (upper curve) determined by backward-integration.

Each element applied to model the room with fittings and installed equipment is defined by its geometry and by the three acoustic parameters absorption index α, transmission index τ and scattering coefficient s (the latter to define the proportion of diffuse and specular reflected energy).

Figure 4 shows the relation between the two first parameters for a plate. The portion τ of the sound energy E impacting from left is transmitted to the right side, and with the absorption α related to the absorption process based on dissipation the portion (1 – τ – α) will be reflected.

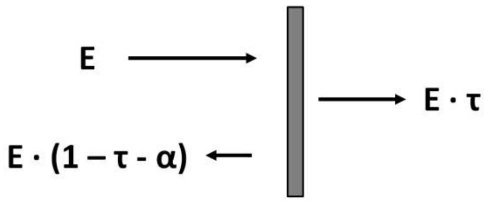

Figure 4: Transmission, absorption and reflection by the vertical plate

The scattering coefficient s describing the part of the diffusely reflected sound influences the direction of the reflected rays left side.

Modelling of the reverberation chamber

The modeled reverberation chamber is a cubic room with an extension of 6 m and therefore a volume of 216 m³ and an inner surface of 216 m². The surfaces are acoustically characterized by an absorption coefficient α of 0,05 and a scattering coefficient of 1 in all frequency bands 125 Hz - 4000 Hz. Due to the totally diffuse reflecting surfaces according to Lamberts law it is not necessary to apply separate diffusers or slanting surfaces to ensure the necessary diffusivity of the sound field.

Figure 5 shows the model of the reverberation chamber with a point source representing the loudspeaker, a receiver point representing the microphone and the expanding cloud of sound particles. Figure 6 shows the particle distribution after many reflections representing the diffuse sound field.

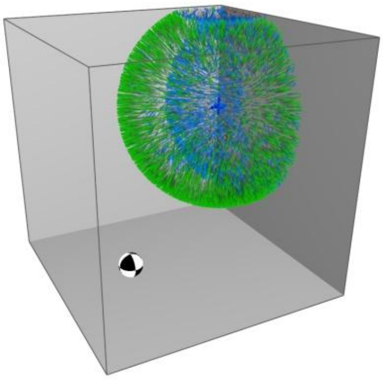

Figure 5: Model of the reverberation chamber with the expanding cloud of sound particles

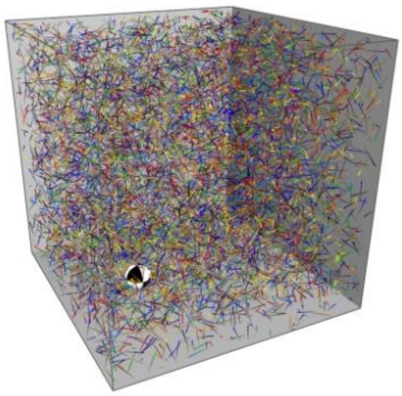

Figure 6: Sound particles after many reflections representing a diffuse sound field

The spread of calculated reverberation times with a simulation with different particle numbers and propagation times showed that the calculation with 1 million particles and a propagation time of 4 seconds is sufficient to ensure the necessary diffusivity - more particles and longer propagation times wouldn't change the calculated results in the frame of the accuracy generally achievable.

Validation of the procedure

The absorption coefficients of products are evaluated in the reverberation chamber by determining the reverberation times with and without the product installed.

Due to the diffuse sound field the expected reverberation time can be calculated according to Eyrings equation (1).

$$T = \frac{V}{4mV - S \cdot \ln\left(1 - \overline{\alpha}\right)} \qquad (1)$$

with

T Reverberation time in seconds
V Volume of the chamber in m³
S Area of the inner surfaces in m²
m Damping index of air
α Mean absorption coefficient

Table 1: Comparison of reverberation times determined by simulation and calculated according to Eyring with equation (1)

	Frequency (Hz)					
	125	250	500	1000	2000	4000
T from simulation	3.15	3.10	3.02	2.92	2.71	2.17
m (20°, 60%) *1000	0.09	0.28	0.64	1.11	2.13	5.86
T from Eyring (1)	3.16	3.10	3.02	2.92	2.71	2.17

The reverberation times determined by simulation with 6 randomly distributed receivers are identically at all receivers in the frame of 0,01 seconds. Table 1 shows the compliance of these reverberation times determined by simulation with those calculated with the Eyring equation (1).

A further validation of the procedure is the determination of the absorption coefficient of a plate installed at the floor of the chamber. The comparison of the absorption coefficient calculated from the reverberation times with the value attached to the plate as input parameter indicates the accuracy of the method.

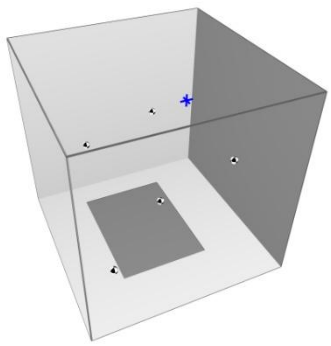

Figure 7: Reverberation chamber with absorbing plate mounted on the floor

The size of the plate is equal to the size of the test arrangement applied in the testing laboratory with the baffle construction described below. To this plate an absorption coefficient of 0.5 is attached for all frequency bands 125 Hz - 4000 Hz. With the reverberation time T_{vor} without and T_{nach} with the plate installed the absorption coefficient according to ISO 354 is calculated from

$$\alpha_p = 0.163 \cdot \frac{V}{S_p} \cdot \left(\frac{1}{T_{nach}} - \frac{1}{T_{vor}} \right) \qquad (2)$$

with

α_P Absorption coefficient of the plate determined from calculated reverberation times

S_P Area covered by the plate in m²

With the reverberation times T_{sim} (table 2) calculated with the SERT-simulation in the "virtual" reverberation chamber the absorption coefficients α_{sim} are calculated with equation (2). The agreement with the input value of 0.5 proves the validity of the applied simulation technique.

Table 2: Absorption coefficients determined from the simulation experiment

	Frequency (Hz)					
	125	250	500	1000	2000	4000
T_{sim} from simulation with plate $\alpha = 0.5$	2.17	2.15	2.11	2.06	1.96	1.66
α_{sim} calculated with equation (2)	0.52	0.52	0.52	0.52	0.51	0.51

These two steps of validation prove that the "virtual" reverberation chamber can be applied to determine the absorption coefficient of different arrangements of absorbing structures.

Modeling of absorbing baffle-systems

As mentioned in the summary, the starting point of this investigation were the absorption coefficients of a baffle system published by a testing institute - a topic that has been covered by a paper [5] published in this journal earlier. The abbreviations for different absorption coefficients defined in this paper shall also be applied in the following.

$\boldsymbol{\alpha_B}$ is the element-specific absorption coefficient. It describes the relation between the absorbed and impacting sound energy, if the element "baffle" is surrounded at all outer surfaces by a diffuse sound field. In a reverberation chamber it could theoretically be determined according to ISO 354, if some baffles would be installed in such a distance from one another and from room surfaces that the diffuse sound field at each elements surface would not be disturbed by adjacent baffles (in practice the possible number of baffles would often be too small in this case to keep the uncertainty of results acceptable). This element-specific absorption coefficient - or the equivalent absorption area A_B if α_B is multiplied with the surface area - is a basic acoustic parameter characterizing a construction integrated from single elements, that is not dependent from the arrangement or denseness of elements in the construction. This parameter is suitable to compare costs and acoustic effectiveness of such single elements.

$\boldsymbol{\alpha_K}$ is the construction-specific absorption coefficient. This construction in the case of a baffle system is an in-line arrangement of vertical oriented baffles, that is characterized by the normalized distance between the row-axes a' = a/h, where a is the distance of the row-axes and h is the height of the baffles. It can be determined in a reverberation chamber according to ISO 354, if a section of the row-construction is surrounded by a reflecting frame and the construction is extended to infinity by specular reflection at the inner surface of this frame. This section is installed far from surfaces so that both sides are exposed to the diffuse sound field (see figure 15 below). This construction-specific absorption coefficient α_K is the quotient of the equivalent absorption area A_K determined from the reverberation times and twice the area S enclosed by the reflecting frame (due to the sound impact from both sides).

$\boldsymbol{\alpha_{KW}}$ as the most important parameter is the absorption coefficient of the baffle system, if it is installed in front of a reflecting plane. This value is also relevant if the baffle-system is suspended from a reflecting ceiling with no relevant absorption above the baffle system. It can be determined in a reverberation chamber according to ISO 354, Annex B.6 as described with mounting condition J. The system with reflecting frame is installed on the reflecting floor of the reverberation chamber (see figure 16 below).

There are three different methods to include such a baffle system in simulation calculations where the noise level at work places shall be predicted in the planning phase of industrial plants or other working areas. Figure 8 shows as an example such a baffle system above a bottling plant modeled for reasons of noise prediction.

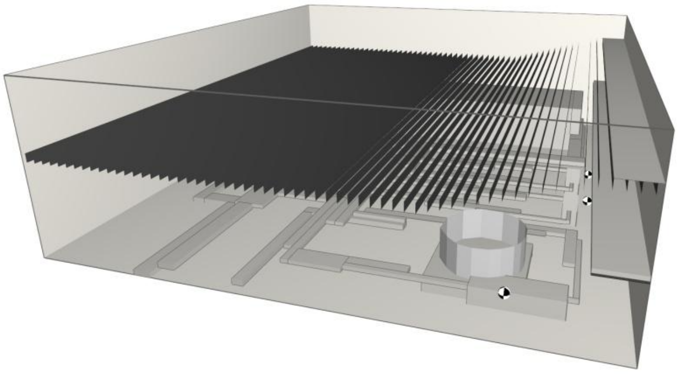

Figure 8: Model of a bottling plant with a baffle-system developed to calculate noise levels at work places

The first and most flexible method is to model each element of the baffle system separately as a vertical plate as it is shown in figures 4 and 8. A scattering coefficient of 0 (specular reflection) and the above mentioned element-specific absorption coefficient α_B (derived from manufacturers product specifications) is attached to each baffle as input parameter. These are the only inputs to define the acoustic properties - the influence of the detailed arrangement follows directly from the detailed modeling according to figure 8. If the transmission index τ is set to 0 the particles impacting on a baffle but not absorbed (portion $1 - \alpha_B$) are reflected specularly into the volume above the construction. Figure 9 shows the transmission of sound particles through the baffle construction in that case.

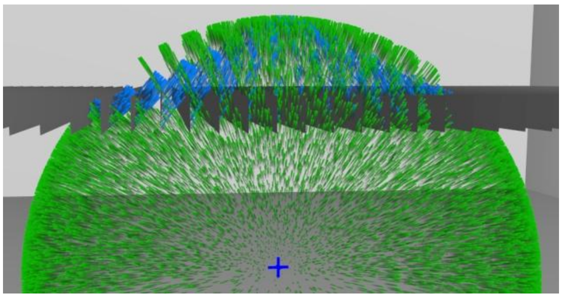

Figure 9: The transmission of sound particles through the baffle construction with $\tau = 0$

If the sound particles impacting on a baffle but not absorbed (portion $1 - \alpha_B$) are transmitted through the baffle ($\tau = 1 - \alpha_B$) the resulting pattern of the transmitted particles develops as it is shown in figure 10.

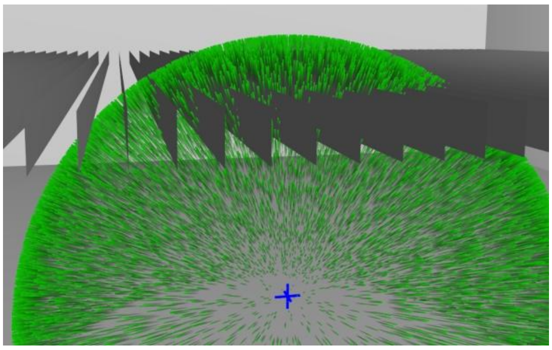

Figure 10: The pattern of transmitted particles with $\tau=1-\alpha_B$

In both cases the sound not absorbed is transmitted to the volume above the baffle system - therefore the acoustic effect of the baffles on the sound pressure levels at work places below is the same in most cases (exception: not uniform distribution of absorption in the volume above this baffle system).

With a second method the complete baffle system is replaced by one single plate with the construction-specific absorption coefficient α_K at both sides and a transmission index of $\tau = 1 - \alpha_K$. According to these input parameters a portion of α_K of all particles hitting the plate are absorbed with each single pass and the remaining portion is transmitted to the opposite side.

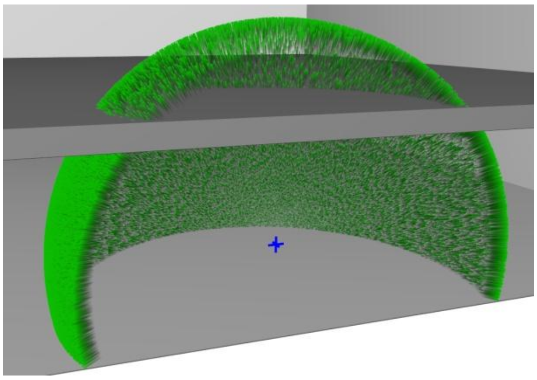

Figure 11: The baffle system is modeled as a plate with an absorption coefficient α_K and a transmission index $\tau = 1 - \alpha_K$

With both methods the portion of sound energy not absorbed by the baffle system is transmitted to the volume above and will be transmitted - passing the construction again - back to the workroom below. This process is repeated with the corresponding loss of sound power with each pass. With these techniques an absorption in the upper volume - e.g. an absorbing coating at the roof underside - will be included correctly.

According to a third method the absorption coefficient α_{KW} - generally documented by the manufacturer as the baffle systems absorption coefficient (and measured according to ISO 354, annex B.6 with mounting arrangement J) - and a transmission index 0 is attached to the single plate similar to method 2 described above. The absorption coefficient α_{KW} describes the absorption of the baffle system with a reflecting surface at one side and therefore related to a double passage of sound through the construction. Therefore the remaining portion of sound energy $1 - \alpha_{KW}$ describes the sound energy reflected to the room.

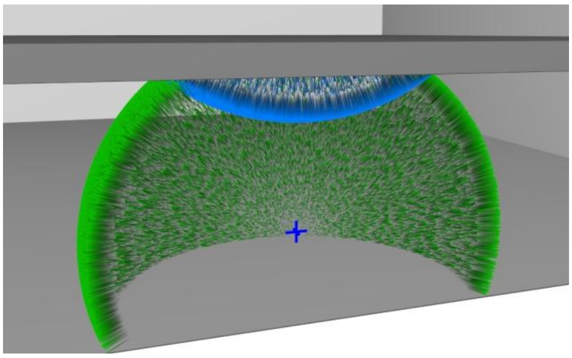

Figure 12: The baffle system modeled as a plate with absorption coefficient α_{KW} and a transmission index 0

If the baffle system is installed directly below the ceiling, it is not necessary to model it as a separate plate as shown in figure 12. In such cases the absorption coefficient α_{KW} can be attached to the fitted part of the ceiling surface directly.
It is obvious that the most flexible method is the first one with a detailed modeling of each baffle. In that case different heights and special arrangements with varying spatial density of baffles and even existing absorption at the ceiling above can be taken into account. Further it is obvious that the visual impression is by far more realistic as it is shown with figure 8 - an aspect that should not be underestimated because it supports the interdisciplinary discussion between acousticians and architects or other planners.

Application of simulation techniques to derive absorption coefficients from values determined with procedures not standardized

With the technique to include a baffle system by modeling each baffle plate separately it is possible to simulate the measurement of any arrangement of baffles in a reverberation chamber, even if this measurement has not been performed with mounting conditions in accordance to the relevant standard ISO 354, to derive the element-specific absorption coefficient α_B on the basis of the reverberation times measured for that construction and then to repeat the simulation with mounting conditions in accordance with the standard.

In the actual case absorption data of a baffle system were presented in the specification sheet - see table 3 - that seemed to be by far too high relative to the existing experience with such systems. From theory [5] and from many measurements it is well known that the maximal possible absorption coefficient with a distance of the row axes of a' = 1 even with an element-specific absorption coefficient α_B = 1 is roughly 0.8 - the values presented by the manufacturer shown in table 3 are not probable.

According to the laboratory report these values in table 3 have been determined with a construction shown in figure 13 in the reverberation chamber. The baffles with dimension 1,2 m x 0,6 m are installed in 10 rows with a distance of 0,4 m between the axes, each row consists of two baffles with a gap of 0,1 m between them. The arrangement is installed in a rack without a reflecting frame around it as it would be required by ISO 354.

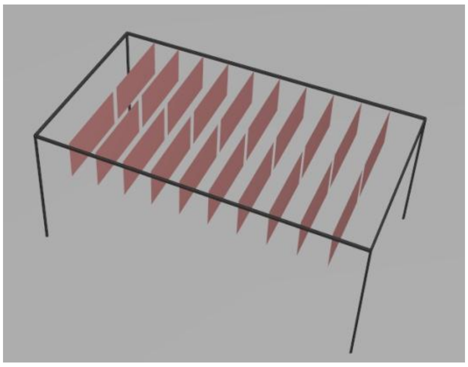

Figure 13: The construction installed in a reverberation chamber according to the laboratory report

Twenty baffles were installed, therefore the equivalent absorption area A of the construction derived from the reverberation times measured was divided by 20 to derive the absorption area per element A* as it was presented in the product data according to table 3. The absorption coefficient α* also presented in the manufacturers product sheet was obtained by dividing the total equivalent absorption area 20A* by the - one sided - area of the construction 10 m².

Table 3: The absorption data presented in the product specification sheet

Determined parameters from the laboratory report	Frequenz (Hz)					
	125	250	500	1000	2000	4000
A* m² per baffle	0.14	0.35	0.62	0.77	0.70	0.47
α*	0.28	0.69	1.23	1.53	1.40	0.94

These values can't be used in simulation calculations directly because the complete construction - even the sides not covered by a reflecting frame according to the standard - were exposed to the diffuse sound field and the resulting absorption was related to the ground projected area of 10 m². Therefore the published absorption coefficients don't describe the absorbed portion of sound energy impacting on the reference surface of 10 m².

In such cases the simulation of the measurement in a reverberation chamber can be applied in the sense of a comparison method to find the corrected absorption coefficients α_{KW} in agreement with ISO 354.

The first step is to model the situation as it was applied by the manufacturer - or the commissioned laboratory - according to figure 14.

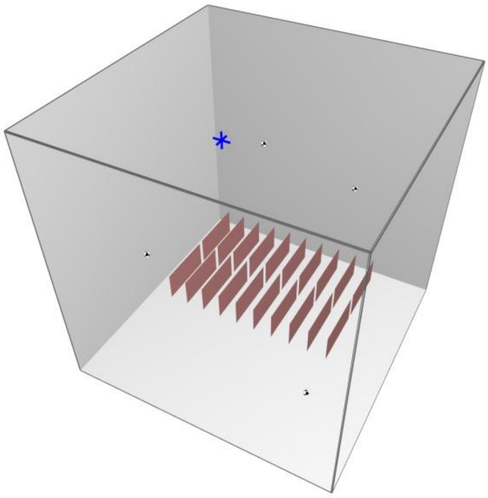

Figure 14: Simulation of the manufacturers measurement in the "virtual" reverberation chamber

Then the element-specific absorption coefficient α_B was varied stepwise in each frequency band till the equivalent absorption area determined with this construction was in agreement with the value obtained in the laboratory. Equation (3) shows the dependency of the element specific absorption coefficient α_B from the total equivalent absorption area A* for this measurement setup.

$$\alpha_B = 0.511 \cdot (A^*)^2 + 0.668 \cdot A^* \qquad (3)$$

The first data-line of table 4 shows these values of α_B - they are now in accordance with existing experience with such systems.

Table 4: The element specific and construction specific absorption coefficients of the baffle system

Kenngrößen	Frequenz (Hz)					
	125	250	500	1000	2000	4000
α_B	0.10	0.29	0.60	0.81	0.72	0.43
α_K	0.12	0.30	0.52	0.63	0.58	0.40
α_{KW}	0.21	0.46	0.72	0.83	0.78	0.60

These element specific absorption coefficients are attached to both sides of each baffle. With these even under acoustic aspects correctly modeled baffles the measurement with mounting conditions in accordance with the standard ISO 354 can be simulated to obtain the correct construction specific absorption coefficients α_K or α_{KW} for this baffle arrangement.

In the arrangement shown in figure 15 the 20 baffles - still floating in the "virtual" reverberation chamber above ground - are enclosed by a reflecting frame. It is modeled with plates with the value 0 attached to the element specific absorption coefficient, the transmission index and the scattering coefficient. The construction specific absorption coefficient α_K in table 4 was calculated as the quotient of the equivalent absorption area determined with this simulation and twice the area enclosed by the frame.

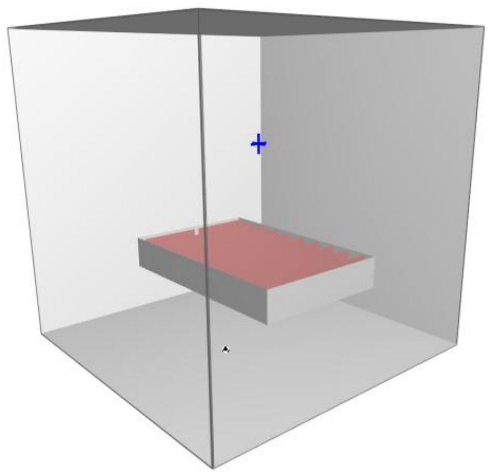

Figure 15: Floating baffle system enclosed by a reflecting frame to determine α_K with the simulation calculation

Further the complete construction is "mounted" directly on the floor as shown in figure 16 and the absorption coefficient α_{KW} is calculated as the quotient of the equivalent absorption area A and the area S enclosed by the frame. These values α_{KW} are in accordance with the requirements of ISO 354 and can be applied in noise prediction calculations with rooms of any size and interior.

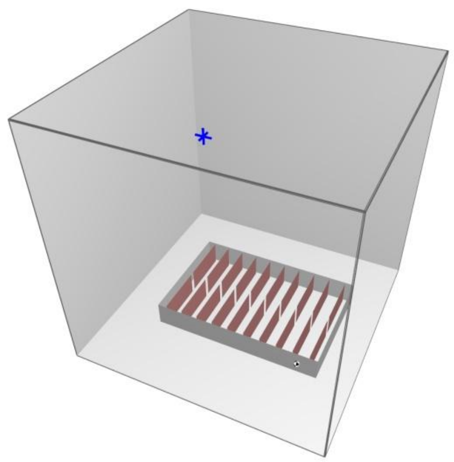

Figure 16: Baffle system enclosed by a reflecting frame and located directly on the floor to determine α_{KW}

This absorption coefficient α_{KW} can directly be applied to characterize the absorption of the ceiling plate if the construction shall be suspended horizontally direct under the ceiling surface.

Application for acoustic planning purposes

This investigation was based on the existence of a diffuse sound field in a reverberation chamber. But even if the absorption coefficients determined that way - may be by measurement or by simulation - are related to the existence of a diffuse sound field, they can be applied in good agreement with experimental results in cases where not diffuse sound field conditions exist.

But there are exceptions. Baffle constructions are often applied in industrial environments like such bottling plants as shown in figure 8 or in other production or packaging plants. Working places of machine operators are often separated from the machine by transparent screens, and in such cases the effect of the screen is often minimized by direct back-reflection of sound from an acoustically hard ceiling surface. The suspension of a baffle system above the machine has only little effect, because the reduction of sound energy passing the baffle construction vertically and therefore parallel to the baffle plates is small. These direction dependent effects are only simulated correctly if the first method - the detailed modeling with each baffle as an own object - is applied. With the plate construction according to method 2 and 3 - see figures 11 and 12 - the angle dependency of the absorption is not included. Therefore it is generally recommended to apply the detailed modeling of baffle systems to include this angle dependent effects.

If product data published by the manufacturer shall be applied as input data in such simulations it is recommended to inspect the laboratory report of the measurement and especially the measurement setup that has been applied. If no surrounding frame was installed only the equivalent absorption area derived from measurements of the reverberation time shall be taken as the reliable "true" value. Applying the described comparison method the absorption coefficients in accordance with ISO 354 can be derived.

Absorption coefficients slightly larger than 1 can certainly result from correct measurements with setups in accordance with the standard. In simulation calculations these values are capped to 1. But if values exceed 1.3 they are a strong indication that no reflecting frame may have been applied. In the practical example being the starting point of this investigation the absorption coefficients declared by the manufacturer (see table 6) may positively be misleading.

Table 6: Comparison of absorption data determined with different mounting conditions.
*) Values > 1 shall be replaced by 1 in acoustic calculations

	Frequency (Hz)					
	125	250	500	1000	2000	4000
A m² per baffle (result testing laboratory)	0.14	0.35	0.62	0.77	0.70	0.47
α of construction (declaration of manufacturer)	0.28	0.69	1.23*)	1.53*)	1.40*)	0.94
A m² per baffle (from simulation with mounting acc. to ISO 354)	0.11	0.24	0.37	0.43	0.40	0.31
α of construction (from simulation with mounting acc. to ISO 354)	0.21	0.46	0.72	0.83	0.78	0.60

Even if the calculated sound pressure levels may not be influenced much due to the capping of these values with 1 the different efficiency in the frequency bands is completely hidden.

The increasing importance and power of simulation techniques produces some requirements with respect to the declaration of absorption data and other parameters of products. Even in standardization these aspects should be taken into account. There are examples of standardized absorption data that cannot be applied if these products are implemented in models for simulations. An example is the German VDI guideline about the sound absorption of suspended ceilings [6]. It defines the absorption of plates installed with gaps between them by relating the total absorption plate + gap to the surface of the plate alone. The result are values by far larger than 1 because the absorbing backside of the plate is acoustically relevant. According to the definition applied these values shall not be capped to keep this additional absorption in the declared information. But this definition neglects that the values must be capped in a simulation calculation because not more sound particles than 100% of the impacting ones can be absorbed. The correct way would be to reference the absorption to an area including the surfaces of plate + gaps.

The simulation techniques described offer many new possibilities to integrate geometrically complex structures like locally varying arrangements of absorbing plates and other objects in the practice of acoustic planning. They allow in many cases to concentrate the measurement in the acoustic laboratory on material or element specific values and to determine the acoustic efficiency of different arrangements of these elements with modeling and simulation techniques. These techniques offer new possibilities, but produce also new requirements in the frame of standardization.

Literature

[1] ISO 354: 2003 "Acoustics - Measurement of sound absorption in reverberation chambers"

[2] CadnaR, Software for the calculation and assessment of sound in rooms, http://www.datakustik.com/produkte/cadnar

[3] Chapter 11.2 in M. Vorländer: "Auralization", RWTHedition, Springer Verlag 2008

[4] Schroeder, M. R.: New Method of Measuring Reverberation Time, J. Acoust. Soc. Am. 37 (1965), 409

[5] Probst W.: "Die Schallabsorption von Kulissendecken", Lärmbekämpfung Nr.2, März 2008, (english version http....Sound Absorption of Baffle Systems)

[6] VDI 3755: 2013 "Sound insulation and sound absorption of suspended ceilings"