Sound Absorption of Baffle Systems

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Dezember 2007

Summary

Baffle systems are applied to ensure an acceptable acoustical climate and to reduce the noise levels in rooms with noisy machinery and work places. While in offices, salesrooms and administrations in most cases closed suspended ceilings are used, baffle systems are often used in machine halls, at production lines and in other technically complex environments.

The absorption coefficient of such baffle systems is not a fixed number – or a spectrum – as it is the case for a flat absorbing plate, but depends on the spacing of the baffle elements. This spacing influences the absorption as well as the costs of such a system, therefore it is important to know the dependence of the absorption coefficient from the detailed and cost relevant construction.

These relations have been developed and are presented in the following. The resulting tables and diagrams can be used to calculate the absorption coefficient of a baffle construction from the absorption coefficient of the plate material. They can also be used to determine from the absorption coefficient of a given baffle system, that may have been measured in a laboratory according to DIN EN ISO 354, the absorption coefficients of the system in a different arrangement.

The derivation is based on the assumption that the transmission of a baffle structure between the elements is geometrically determined – this assumption has proven to be a good approximation in many cases where baffle heights are comparable to the distance between the rows. It is not applicable for baffled silencers where the spacing between the baffles is small and the wave character of sound determines the attenuation.

Introduction

Baffle systems are often used to reduce the noise in production areas with high humidity and special hygienic requirements where the application of plane suspended ceilings is problematic.

Figure 1 Sound absorbing baffles in a bottling plant

But it is difficult to assess the effectivity of such baffle systems, if no absorption measurements have been made with exactly the baffle spacing that shall be used in the actual case. It can easily be shown

that the linear addition of the equivalent absorption area of single baffles is unsuitable and overestimates the absorption of the baffle system. In many cases the manufacturer prides data related to a certain baffle spacing that have been measured according to IS 354 /1/ – but there the question arises how to determine the absorption of the construction if a different spacing shall be used.
This paper is based on earlier investigations of the same topic /2/ and the presented relations between technical parameters and absorption of a baffle system have been applied in many cases – they are an excellent approximation and can be recommended to be used to calculate the reduction of noise levels or reverberation times in planning cases

The sound absorption of baffle systems

In the following the absorption coefficient of a linear array of baffles installed in front of a reflecting surface – e. g. under a concrete ceiling – is derived.
Starting point ist he absorption coefficient of the absorption plate. It is assumed – as a good approximation as it is shown later – that sound transmission through such a configuration is mainly determined geometrically.
From baffle height h and the spacing of the center lines a the related spacing a' is determined

$$a' = \frac{a}{h} \qquad (1)$$

The coordinate x' is also used as a relative value related to the baffle height

$$x' = \frac{x}{h} \qquad (2)$$

The thickness of the baffles is assumed to be negligible related to the spacing.

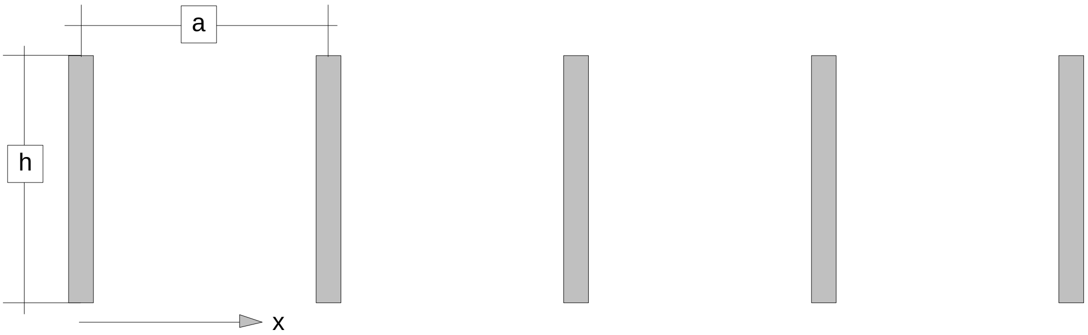

Figure 2 Cross section of the baffle construction

At the lower „entry“- surface of the construction an approximately diffuse sound fiel dis assumed, this means that sound rays penetrate the construction with the same probability from all directions

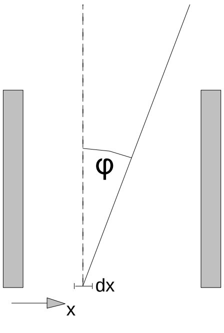

Figure 3 Sound rays traversing a window dx with angle φ

With an energy density E of the sound field below the baffle construction in the room the sound power dP’ is radiated into an angle dφ from a window of width dx with an extension of one length unit vertical to the paper plane

$$dP' = c \cdot E \cdot \frac{d\varphi}{2\pi} \cdot dx \cdot \cos(\varphi) \qquad (3)$$

The sound power radiated through the window dx from all directions into the baffle system is

$$P' = \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} c \cdot E \cdot \frac{d\varphi}{2\pi} \cdot \cos(\varphi) dx = \frac{c \cdot E \cdot dx}{\pi} \qquad (4)$$

This last relation can be used to calculate the length related sound power radiated through a window dx at position x and crossing the baffle construction free without being reflected and with absorption

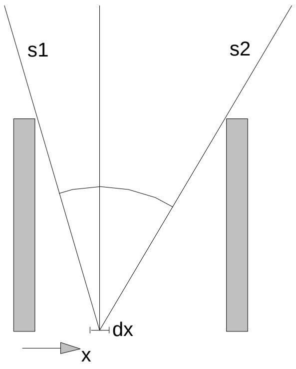

Figure 4 Sound rays crossing the window dx and the baffle system without being reflected

This sound power is determined by

$$dP_0' = \int_{arctg(-x')}^{arctg(a'-x')} c \cdot E \cdot \frac{dx'}{2\pi} \cdot h \cdot \cos(\varphi) d\varphi \qquad (5)$$

Performing this integral yields

$$dP_0' = \frac{c \cdot E \cdot h \cdot dx'}{2\pi} \cdot \left(\frac{a' - x'}{\sqrt{1 + (a' - x')^2}} + \frac{x'}{\left(1 + x'^2\right)} \right) \qquad (6)$$

Performing another integration over the complete lower entry-window yields the sound power that enters the construction from the room side and leaves it without being reflected or attenuated by absorption.

$$P'_{0,aus} = \frac{c \cdot E \cdot h}{2\pi} \cdot \left(\int_0^{a'} \frac{a' - x'}{\sqrt{1 + (a' - x')^2}} dx' + \int_0^{a'} \frac{x'}{\sqrt{1 + x'^2}} dx' \right) \qquad (7)$$

With appropriate substitution we get

$$P'_{0,aus} = \frac{c \cdot E \cdot h}{\pi} \cdot \left(\sqrt{1 + a'^2} - 1 \right) \qquad (8)$$

According to (4) the total length related sound power entering through a window of width a is

$$P'_{in} = \frac{c \cdot E \cdot a}{\pi} \qquad (9)$$

If the rays striking a baffle are completely absorbed the absorption coefficient for sound traversing the system is calculated wit (8) and (9) from

$$\alpha_K = \frac{P'_{in} - P'_{out}}{P'_{in}} = 1 - \frac{P'_{out}}{P'_{in}} \qquad (10)$$

Even with the best possible absorption coefficient 1 of the baffle plate the absorption coefficient of the construction is

$$\alpha_K = 1 - \frac{\sqrt{1 + a'^2} - 1}{a'} \qquad (11)$$

To find the frequency dependent absorption of the baffle system it is necessary to take the rays into account that strike the baffles and therefore don't cross the construction without absorption. Generally a ray or the attenuated sound energy can cross the baffles as it is shown at the right side of figure 5 or it can be reflected as it is shown at the left side. The two cases are identical if we are only interested in sound powers and directions, because the left presentation can be transformed to the right one by folding up the ray path.

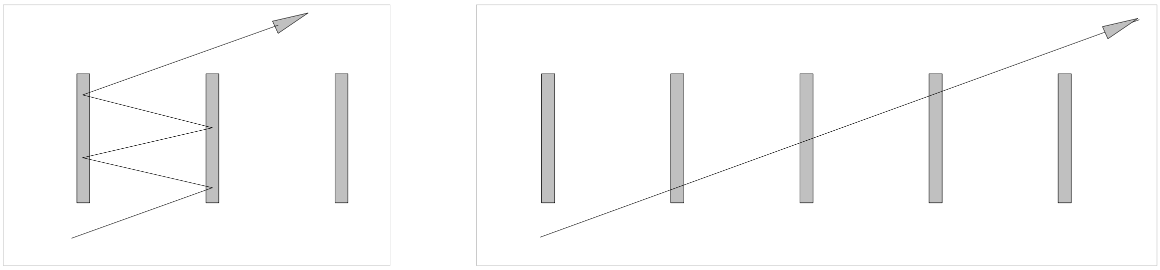

Figure 5 Baffles that reflect (left) or transmit (right) the sound power not absorbed

Therefore it has no consequence for the following discussion if the sound not absorbed penetrates through the baffles or is reflected back and forth. Only the absorption coefficient α_B is important where α_B defines that portion of the sound power striking the baffles that is absorbed.

Figure 6 shows the geometry used in the following.

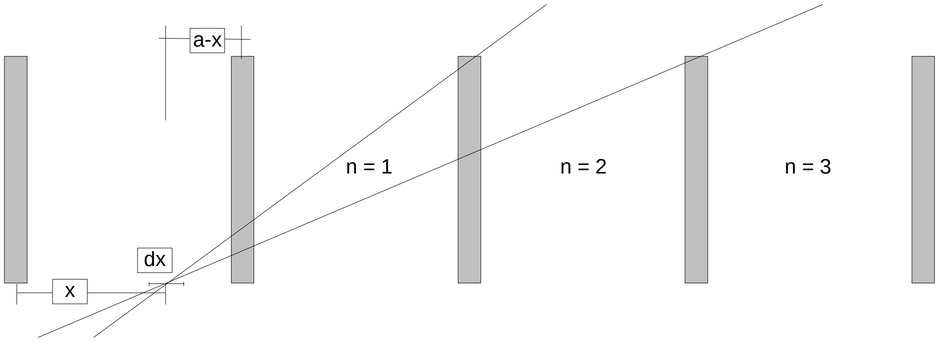

Figure 6 Cone of rays crossing the window dx and being attenuated by absorption twice.

The length related sound power entering the construction through the window dx and leaving the construction n segments away can be determined by integration over all angles between the rays connecting the window dx with the upper edges of the baffles.

$$dP'_{n,1} = (1-\alpha_B)^n \cdot \frac{c \cdot E \cdot h \cdot dx'}{2\pi} \cdot \int\limits_{arctg(n \cdot a' - x')}^{arctg((n+1) \cdot a' - x')} \cos(\varphi) d\varphi \qquad (12)$$

Taking into account the symmetry of the problem and for each number n two exit windows left and right with n baffles to be crossed we get

$$dP'_{n} = (1-\alpha_B)^n \cdot \frac{c \cdot E \cdot h \cdot dx'}{\pi} \cdot \int\limits_{arctg(n \cdot a' - x')}^{arctg((n+1) \cdot a' - x')} \cos(\varphi) d\varphi$$

After integration and some transformation the result is

$$dP'_{n} = \frac{c \cdot E \cdot h}{\pi} \cdot (1-\alpha_B)^n \cdot \left(\int_0^{a'} \frac{(n+1) \cdot a' - x'}{\sqrt{1+((n+1) \cdot a' - x')^2}} dx' - \int_0^{a'} \frac{n \cdot a' - x'}{\sqrt{1+(n \cdot a' - x')^2}} dx \right) \qquad (13)$$

A further integration over x’ in the lower entry window can also be performed using an appropriate substitution. The result is the length related sound power leaving the system after n absorption processes

$$P'_{n} = \frac{c \cdot E \cdot h}{\pi} \cdot (1-\alpha_B)^n \cdot \left(\sqrt{1+((n-1) \cdot a')^2} + \sqrt{1+((n+1) \cdot a')^2} - 2 \cdot \sqrt{1+(n \cdot a')^2} \right) \qquad (14)$$

After summation over all upper exit windows, addition of the sound transmitted without absorption according to (8), relating this transmitted sound power to the entering sound power according to (9) and applying (10), the absorption coefficient of a baffle system for single sound transmission is

$$\alpha_K = 1 - \frac{\sqrt{1+a'^2}-1}{a'} - \frac{1}{a'} \sum_{n=1}^{\infty} (1-\alpha_B)^n \cdot \left(\sqrt{1+((n-1) \cdot a')^2} + \sqrt{1+((n+1) \cdot a')^2} - 2 \cdot \sqrt{1+(na')^2} \right)$$

(15)

Equation (15) can be programmed and evaluated for any combination of parameters..

Starting point for a calculation of the absorption coefficient of a baffle system with a certain related spacing a’ with equation (15) is the absorption coefficient α_B of the absorption plate. This absorption coefficient describes the portion of the sound powert hat is absorbed if the rays strike the plate.

If an absorption plate shall be used to construct a baffle system the first step should be to measure the frequency dependent absorption coefficient of the plate material in a reverberation chamber according to EN 354. The plate should not be installed in the usual way parallel to the floor with a little distance as it is done to perform such measurements for suspended ceilings, but as it is shown in figure 7 in an upright position. Some plates are located in a distance from one another that a diffuse sound field is realised at both sides of each plate. The edges of the plates should be covered with reflecting slats.
Measuring the reverberation time with and without the plates installed, the equivalent absorption area A of all plates is calculated in one third octave bands according to ISO 354.

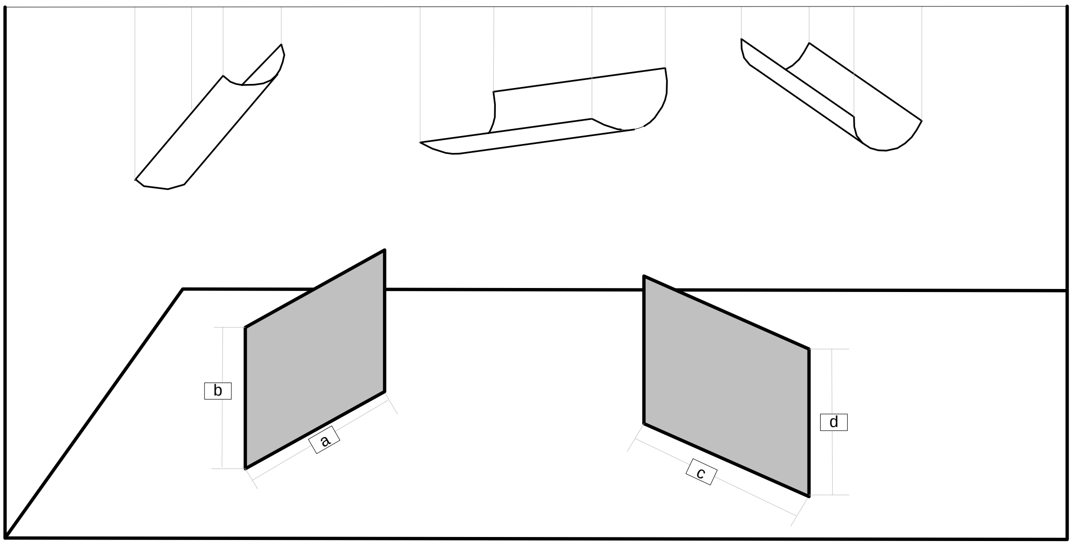

Figure 7 Measuring the absorption coefficient α_B of the absorbing plates

The absorption coefficient of the absorbing plates is calculated by dividing the determined equivalent absorption area through all surfaces of the plates – with the example shown this is

$$\alpha_B = \frac{A}{2 \cdot a \cdot b + 2 \cdot c \cdot d} \qquad (16)$$

From equation (15) the absorption coefficient α_K of the baffle system with related spacing a’ is calculated for each frequency band. Principally this absorption of the baffle system could have been measured in the reverberation chamber using the arrangement shown in figure 8, where the baffles are installed in a reflecting frame and located in a way that a diffuse sound field can be assumed at both sides. Even in this case the eqivalent absorption area determined must be divided by twice the area inside the reflecting frame to account for sound transmission in both directions.

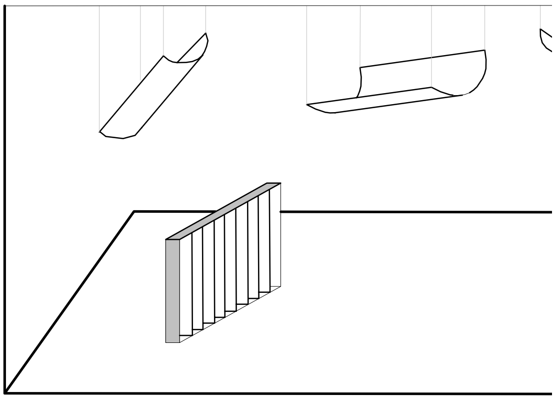

Figure 8 Measuring the absorption coefficient α_K in the reverberation chamber

If the baffle system is suspended below a reflecting ceiling, the rays penetrate through the construction twice. This second absorption process has to be taken into account.

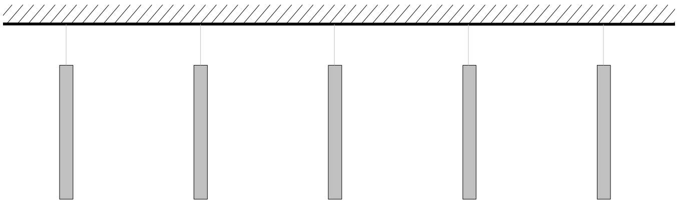

Figure 9 Baffle system suspended under a reflecting ceiling

This absorption coefficient $\alpha_{K,W}$ of the baffle system in front of a reflecting surface is

$$\alpha_{K,W} = \alpha_K \cdot (2 - \alpha_K) \qquad (17)$$

Finally we take into account that the surface behind the baffle system is absorbing and can be characterized by an absorption coefficient α_H . This is the case if the poor absorption of baffle systems at lower frequencies shall be improved by a backward gypsum plate with damped air gap or if some absorbing plaster is applied.

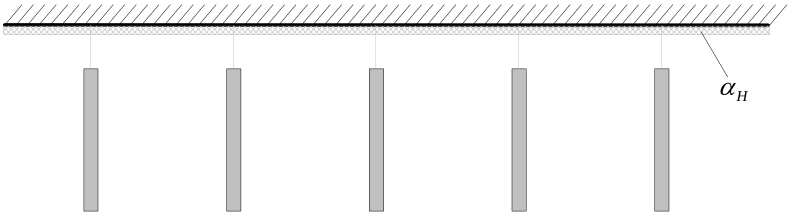

Figure 10 Baffle system suspended under a ceiling with absorption coefficient α_H

The absorption coefficient of the construction with baffle system and backing with absorption coefficient α_H is

$$\alpha_{Komb} = \alpha_{K,W} + \alpha_H \cdot (1 - \alpha_{K,W}) \qquad (18)$$

Determination of the absorption of baffle systems from material and construction parameters

Equations (15) and (17) have been evaluated with variation of the absorption coefficient α_B of the plate material and the related baffle spacing a'. Table 1 contains the absorption coefficients for single sound transmission. From these the absorption coefficients $\alpha_{K,W}$ with the baffle system suspended under a reflecting ceiling are calculated and presented in table 2.

Table 1
Absorption coefficient α_K of a baffle system for single sound transmission with plates characterized by an absorption coefficient α_B and with a height related spacing of a' with diffuse sound field applied.

alfa_B	**Related baffle spacing a'**								
	0.4	**0.6**	**0.8**	**1**	**1.2**	**1.4**	**1.6**	**1.8**	**2**
0.1	0.19	0.14	0.11	0.09	0.08	0.07	0.06	0.05	0.05
0.2	0.32	0.24	0.20	0.16	0.14	0.12	0.11	0.10	0.09
0.3	0.43	0.33	0.27	0.23	0.20	0.18	0.16	0.14	0.13
0.4	0.51	0.41	0.34	0.29	0.26	0.23	0.21	0.19	0.17
0.5	0.58	0.48	0.40	0.35	0.31	0.28	0.25	0.23	0.21
0.6	0.64	0.54	0.46	0.40	0.36	0.32	0.29	0.27	0.25
0.7	0.69	0.59	0.51	0.45	0.40	0.36	0.33	0.30	0.28
0.8	0.74	0.64	0.56	0.50	0.45	0.41	0.37	0.34	0.32
0.9	0.77	0.68	0.61	0.54	0.49	0.45	0.41	0.38	0.35
1	0.81	0.72	0.65	0.59	0.53	0.49	0.45	0.41	0.38

Table 2
Absorption coefficient $\alpha_{K,W}$ of a baffle system with plates characterized by an absorption coefficient α_B and with a height related spacing of a' suspended under a reflecting ceiling with diffuse sound field in the room.

alfa_B	**Related baffle spacing a'**								
	0.4	**0.6**	**0.8**	**1**	**1.2**	**1.4**	**1.6**	**1.8**	**2**
0.1	0.35	0.26	0.21	0.17	0.15	0.13	0.11	0.10	0.09
0.2	0.54	0.43	0.35	0.30	0.26	0.23	0.21	0.19	0.17
0.3	0.67	0.56	0.47	0.41	0.36	0.32	0.29	0.27	0.25
0.4	0.76	0.65	0.57	0.50	0.45	0.40	0.37	0.34	0.31
0.5	0.82	0.73	0.65	0.58	0.52	0.48	0.44	0.40	0.37
0.6	0.87	0.79	0.71	0.64	0.59	0.54	0.50	0.46	0.43
0.7	0.90	0.83	0.76	0.70	0.65	0.60	0.55	0.52	0.48
0.8	0.93	0.87	0.81	0.75	0.70	0.65	0.60	0.57	0.53
0.9	0.95	0.90	0.85	0.79	0.74	0.69	0.65	0.61	0.58
1	0.96	0.92	0.88	0.83	0.78	0.74	0.69	0.65	0.62

An example fort he application of table 1 is shown in figure 11 – the left part of the room with sound sources is separated from the other part of the room at the right side by an opening and baffles shall be applied in this opening to reduce sound transmission.

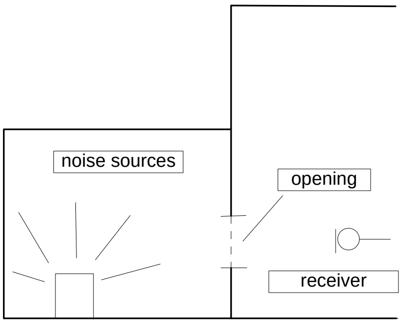

Figure 11 Separation of sound sources from the main room by an opening with baffles.

The level in the main room caused by the sources is L_{open}, after installation of the baffle system L_{baffle}, and the noise reduction is therefore

$$\Delta L = L_{open} - L_{baffle}$$

This reduction can be calculated with absorption coefficients α_K according to table 1 from

$$\Delta L = -10 \cdot \lg(1 - \alpha_K) \qquad (19)$$

Table 3 shows this reduction in dependence of the parameters of the baffle material and configuration..

Table 3 Reduction in dB with baffle system installed in the transmission path (diffuse sound field at source side)

alfa_B	**Related baffle spacing a'**								
	0.4	**0.6**	**0.8**	**1**	**1.2**	**1.4**	**1.6**	**1.8**	**2**
0.1	0.9	0.7	0.5	0.4	0.3	0.3	0.3	0.2	0.2
0.2	1.7	1.2	0.9	0.8	0.7	0.6	0.5	0.5	0.4
0.3	2.4	1.8	1.4	1.1	1.0	0.8	0.8	0.7	0.6
0.4	3.1	2.3	1.8	1.5	1.3	1.1	1.0	0.9	0.8
0.5	3.8	2.8	2.2	1.9	1.6	1.4	1.2	1.1	1.0
0.6	4.4	3.3	2.7	2.2	1.9	1.7	1.5	1.3	1.2
0.7	5.1	3.9	3.1	2.6	2.3	2.0	1.8	1.6	1.4
0.8	5.8	4.4	3.6	3.0	2.6	2.3	2.0	1.8	1.6
0.9	6.5	5.0	4.1	3.4	2.9	2.6	2.3	2.1	1.9
1	7.2	5.6	4.5	3.8	3.3	2.9	2.6	2.3	2.1

If baffles are used that way and only absorption coefficents of the system measured in front of a reflecting surface – as generally given by the manufacturer – are available the relevant noise reduction is calculated from

$$\Delta L = -5 \cdot \lg(1 - \alpha_{K,W}) \qquad (20)$$

A typical and frequently arising problem in industrial applications is to determine the absorption coefficients for a planned configuration $a'_{planned}$ from the absoption coefficients published for another spacing a'_{given}. This can be done with a simple interpolation program based on table 2 or with figure 12 for each frequency band separately.

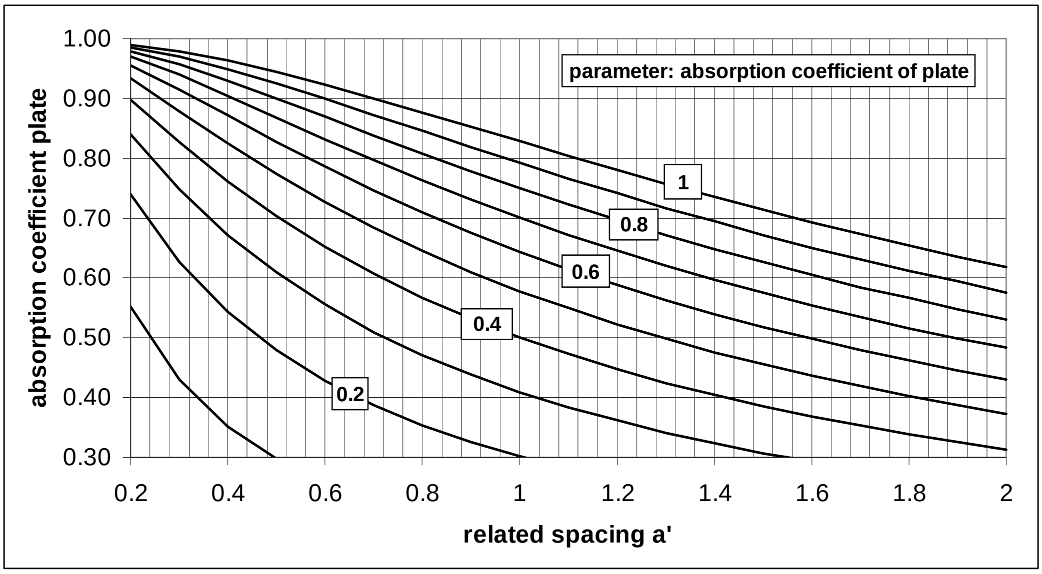

Figure 12 Absorption coefficient of a baffle system suspended under a reflecting ceiling according to table 2

Diagram figure 12 allows simply to calculate from the absorption coefficient with one baffle spacing the absorption coefficient for another spacing.

Example:
The absorption coefficient of a baffle system with baffle height 50 cm at 1000 Hz with baffle spacing 50 cm (related spacing a’ is 1) is according to the manufacturers certificate 0.8. The absorption coefficient with double spacing (a’ = 2) shall be determined.

Solution:
The intersection of the vertical at the abscissa 1 with the horizontal line at the ordinate 0.8 defines the plate absorption 0.9 (parameter of the nearest curve). From this curve the absorption coefficient 0.5 to 0.6 is determined at the abscissa 2.

Many problems can be solved using these results if systems shall be optimized taking into account costs and effects. A simple example is the frequently asked question if it is with respect to noise reduction better to use an absorbing plate material as horizontally closed suspended ceiling or to cut it in stripes and hang these down vertically as baffle system.

If a plate with absorption coefficient 1 is cut in stripes and these are rotated by 90 degree, a baffle system with a related spacing of 1 is produced.
As it is shown in table 2, the absorption coefficient of the baffle system is 0.83 in this case. This is in accordance with many measurements of baffle systems in the reverberation chamber, if the system has been installed in a reflecting frame – in the frequency bands with the best possible absorption a value of about 0.8 is not exceeded (figure 13).

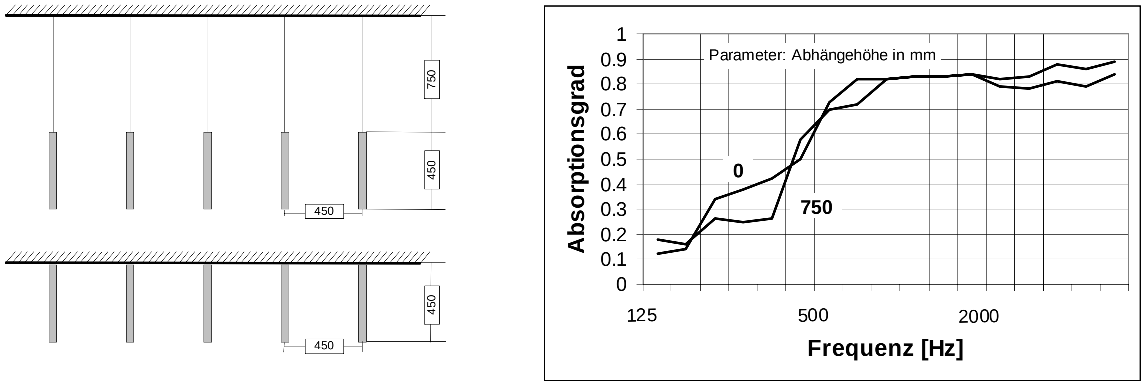

Figure 13 Measured absorption coefficients with a’ = 1 and distance to the ceiling 0 and 750 mm

The open channels where the sound can cross the construction without being absorbed reduce the absorption coefficient – a value of 1 is not possible even in cases where the plate itself is an ideal absorber.
The fact that both surfaces absorb sound if the stripes are oriented vertically comes into play if the absorption coefficient of the plate itself is lower. Table 2 shows that a plate with absorption coefficient lower than 0.7 the baffle system absorbs better than the horizontal plate

Table 2 shows that it’s expensive to compensate a not perfect absorption by a more dense arrangement of baffles. If the mass of material is doubled by using half of the baffle spacing in the example above, the absorption coefficient is increased from 0.83 to 0.94 – this is an increase of the installed equivalent absorption area by 13 % with nearly doubling the costs.

There are a lot of good reasons to apply baffle systems, especially if noise reduction in production and other industrial areas is needed. With the relations presented different possible solutions can be evaluated and optimized.

Literature

/1/ ISO 354:2003 :Measurement of sound absorption in reverberation chambers
/2/ Probst, W.: Optimaler Einsatz von Schallabsorptionsmaterialien – Bewertung der Wirksamkeit für spezielle Anwendungsfälle, Kennwerte und Marktübersicht, in VDI-Bericht 437, VDI-Verlag GmbH, Düsseldorf, 1982