REDUCING NOISE AND OPTIMIZING SOUND WITHIN WORKING SPACES

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Caused by various studies underlining the negative effects of noise exposure and insufficient sound quality within workspaces, this topic receives a growing public attention. These negative impacts include stress symptoms, cardiovascular problems, communication problems and a reduced productivity. In contrary to environmental noise problems caused by infrastructure (aircraft noise, road noise etc.), the responsibility of noise problems within work spaces is distributed among millions of different companies which all require individual solutions. In order to tackle this problem, the German Ministry of Commerce commissioned a project with the objective to develop a procedure to efficiently assess the acoustical situation within workspaces and as a second step to enable the analysis of different measures for improvement. Next to the assessment of noise, various psychoacoustic parameters like the STI or the CI (clarity index) needs to be analyzed. The modeling of complex machinery, speaker systems or people as a sound source must be enabled in order to meet the given objective. At the same time the process should facilitate the comparison of various measures for noise reduction like screens, absorbing baffle ceilings or different workshop layouts. Furthermore and in order to enable a wide base of usage, this procedure needs to be accurate and at the same time easy to apply. This paper provides an overview of research problems, possible solutions and existing techniques.

1. Introduction

The prediction of noise levels at workplaces in the planning phase of industrial plants with machinery and other noise relevant facilities is – or could be – an invaluable support to ensure lowest possible noise levels according to the state of the art or achievable with a given budget. Prerequisite is the application of methods detailed enough to include the most important properties and describing parameters of the plant and the environment that can be influenced to reduce the noise.

The application of prediction methods is common practice with noise from industrial plants producing noise exposure in close-by residential areas. Gas turbine power plants, wind turbines or other noise relevant industrial facilities with critical distance to dwelling zones are generally not planned and installed in developed countries before a prediction calculation has shown that maximal acceptable sound levels will not be exceeded. If this is not the case additional measures can be taken into account and the process may be repeated.

The prediction of occupational noise – this means the prediction of noise levels at work places - is by far more difficult than to predict noise levels in residential areas outside because
- the distances between work place and machine are small relative to the extension of the source
- machines and other technical equipment are often very complex noise sources

- work places and radiating facilities are in most cases inside rooms, and full 3D-calculations of many reflected sound contributions must be taken into account.

Nevertheless an effective software strategy adapted to the problems of occupational noise is now available and shall be presented in the following.

2. The general strategy to include the noise aspect in planning activities

Planning of technical facilities with respect to noise can only be effective if the different contributions to the resulting noise level at a work place are separated and treated separately.

2.1 The Sources

The output of sound energy of noise sources like machines or other technical facilities is acoustically described sufficiently by one single number – the sound power level L_{WA} (ISO 3740 – series, e.g. /2/). This value is a property of the source and independent from the environment where the source is located. It describes the sound radiated into all directions.

If a work place, e.g. an operator position, is connected with a machine, the emission sound pressure level L_{pA} (ISO 11200 – series, e.g. /3/) gives additional helpful information to characterize the source. It is the sound level the machine would produce in free field, this means if operated with free space and no other noise sources around it.

It is obvious that the underlying operating conditions must thoroughly be defined and documented.

These two values LWA and LpA, both numbers with the unit dB(A), should be included for each noise relevant machine and device in specifications and noise declarations (ISO 4871 (4/) by the suppliers and finally in contracts of purchase. In cases of assumed violation of given guarantees the verification can be performed with measurements according to the above mentioned standards.

The list with these two levels serves as input list for the computerized simulation of the plant to calculate the noise levels at the work places with the complete plant in its industrial environment is operated.

2.2 The Room

With machines and industrial plants critical with respect to noise specifications for the room shall be set in force. Critical means that it is known from experience, e.g. from other similar installations, that noise levels at work places with the plant in typical operation may exceed specified noise limits – e. g. 85 dB(A).

Such specifications shall be independent from the noise emission of the plant and shall only define the acoustic properties of the room. Suitable values are the level decrease per doubling of distance DL2 and level excess DLf (defined in ISO 14257/5/).

The prediction methods described in the following allow to check in advance if the target values for DL2 and DLf will not be exceeded with the given room geometry or if absorbing ceilings or other installations are necessary.

The supposed absorption coefficients of the absorbing surfaces applied as input parameters in the simulation calculation shall be included in the contract of purchase of the products as guaranteed properties.

In cases of assumed violation of given guarantees the first step verification can be performed by measuring the spatial decay curve according to ISO 14257. If the predicted values of DL2 and DLf are exceeded, 10 m² of the installed absorption surfaces should be dismounted to determine the absorption coefficient in a reverberation chamber according to ISO 354 /6/.

2.3 Prediction of noise levels at work

The above mentioned parameters to quantify the sound emission of machinery and other technical devices and the absorption properties of the room surfaces are the input parameters for a simulation to calculate the sound pressure levels at work places if the plant is in typical operation. Based on these new and now available software tools acoustic important phenomena like screening, absorption, scattering and transmission through light structures can be taken into account. Noise abatement measures can thus be included stepwise to get the economically most advantageous solution with all the noise specifications fulfilled. This process shall certainly be performed by acoustically experienced engineers knowing about the product solutions and the software application.

3. The software strategy to predict noise levels

There are two fundamentally different approaches to calculate sound propagation inside rooms with many reflections influencing the sound pressure levels at receiver positions. The first method is ray based and all the possible ray paths from source to receiver must be constructed to get the final result. If a ray between source and receiver is reflected n-times, this is a reflection of n-th order.

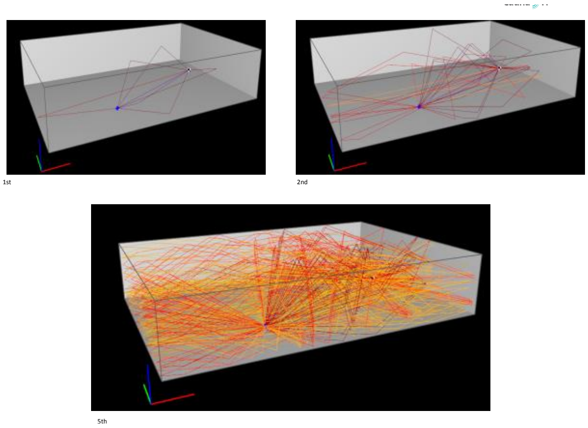

Figure 1: Rays constructed with the mirror image method

Figure 1 shows upper left the direct ray and 6 rays of 1st order, upper right all rays of 1st and 2nd order and in the lower part all reflected rays up to 5th order. The advantage of the ray based methods is that sound attenuation by screening can relative simple be taken into account.

This exponential increase of calculations necessary with higher reflection orders – and the more reverberant a room, the more reflection orders have to be taken into account – is by far less dramatic with the particle model demonstrated in figure 2.

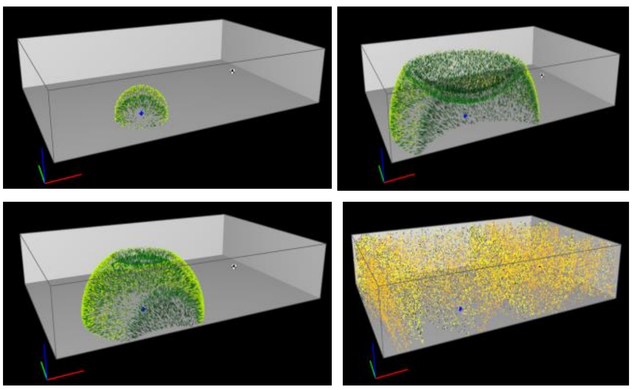

Figure 2: Sound propagation simulated with the particle method

Thousands or even millions of “sound-particles” are radiated statistically distributed in all directions from the sound source and follow a straight propagation line between the reflections at surfaces from the room or from other objects.

The most important step in the process of noise prediction for planned industrial plants with machinery is the modeling – the layout with all geometrical and acoustical parameters relevant for the resulting noise levels must be transferred into a virtual model.

Small machines and devices like the press shown in Figure 3 are simulated by a simple point source.

Figure 3a: Press radiating sound

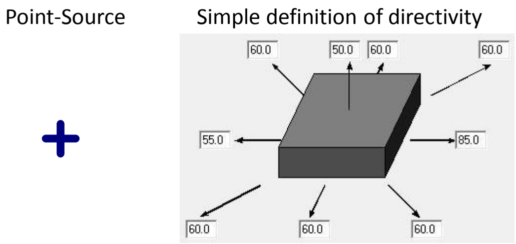

Figure 3b: Simulation by a simple point source with information about directivity

The location in the room is defined by the coordinates x, y and z and the acoustic emission by the above mentioned standardized values L_{WA} and L_{pA}.

The filling machine shown in figure 4 is enclosed in a light casing for security reasons – sound is radiated from a larger surface and produces a sound field that cannot be simulated by a small point source.

Figure 4: Filling machine in a bottling plant

Figure 5 shows some examples for the simulation of such larger box type machines. The box can have any size and even be elevated to allow sound particles propagating underneath.

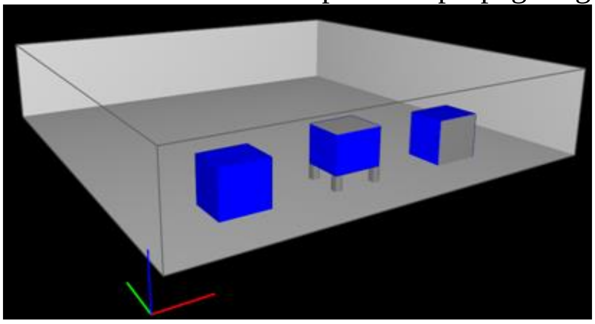

Figure 5: Simulation of three box-type machines with different surfaces radiating sound

With the combination of point sources, line sources and such box-type structures machines of any complexity can be modeled. Figure 6a shows a large bottle washing machine in a bottling plant and figure 6b the corresponding 3D-model.

Figure 6a: Large washing machine in a bottling plant

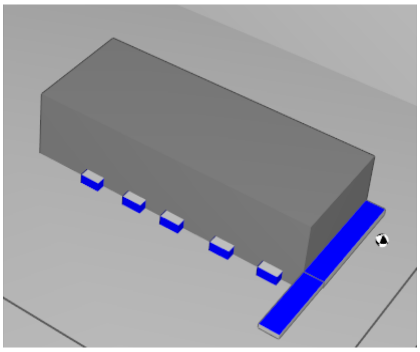

Figure 6b: Computer model of the washing machine

The easy assembly of such machines from basic elements is an important property of simulation software that shall be used frequently for noise prediction. The emission values LWA and LpA are applied as a lump information for the sound emission and the emission of all the partial sources must be adapted automatically to these input data.

The paths of the sound particles emitted from the noise relevant machine parts as shown in figure 7 are calculated taking into account that the massive body of the machine is acoustically opaque.

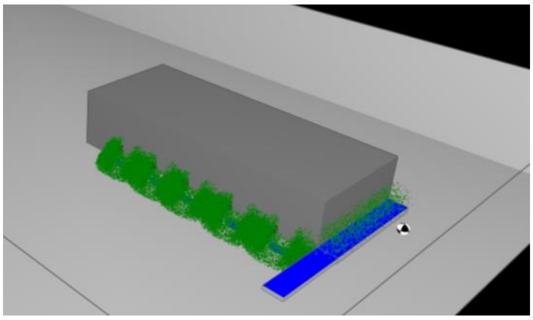

Figure 7: Sound particles are emitted from the noise relevant parts of this machine

The distribution of sound pressure levels in a room are calculated by counting the number of particles that cross a little control volume around the receiver. Figure 8 shows the room split up in such box-type control volumes or “voxels”.

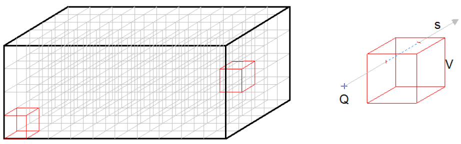

Figure 8: Subdivision of the room in “voxels” to count the crossing particles

Figure 9a shows the machine located in the middle of a room, figure 9b the distribution of calculated sound pressure levels with walls and ceiling completely absorbing thus simulating free field propagation. The yellow colour at the backside of the massive machine indicates the low noise levels due to the screening effect of the massive machine body. With figure 9c walls and ceiling are assumed to be reflective and calculations up to high reflection orders have been performed. The level distribution is by far more smooth caused by the additional sound- immission due to high order reflections inside this room.

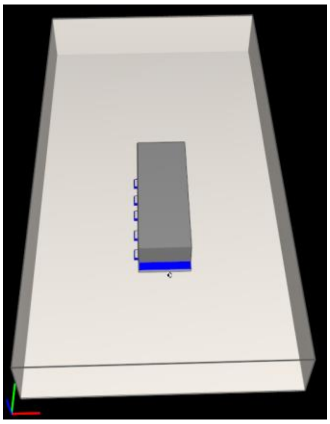

Figure 9a: Machine inside room

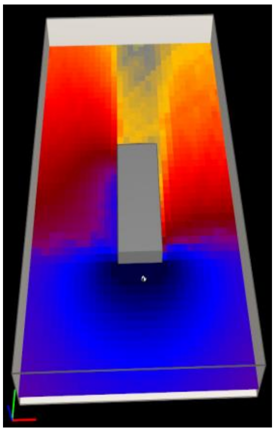

Figure 9b: Level distribution with absorbing walls and ceiling

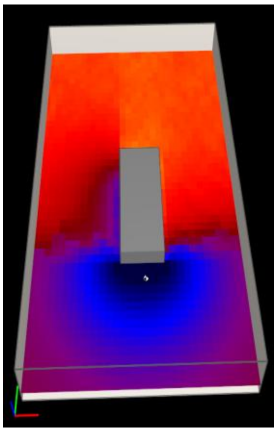

Figure 9c: Level distribution with reflecting walls and ceiling

The big advantage of the method presented is the possibility to integrate locally effective noise reduction measures and to check their effect on receiver levels.

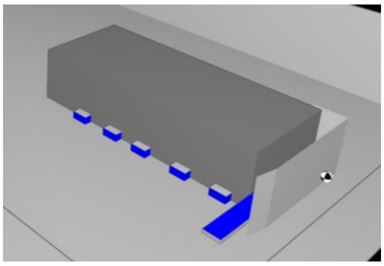

Figure 10a: Transparent screen between workplace and machine

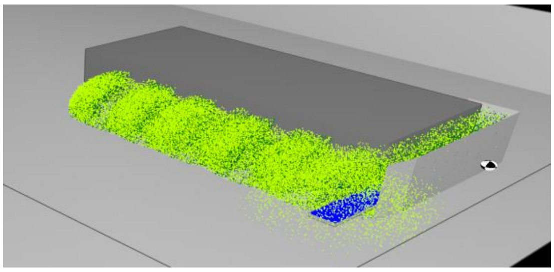

Figure 10b: Sound particles reflected by the screen

Figures 10a and 10b show as an example the protection of the work place by an optically transparent screen, serving as a noise barrier to lower the sound exposure at this position. It is even possible to integrate an absorbing baffle system above the barrier to reduce the sound reflected by the ceiling – figure 11 shows the penetration of sound particles through such an open structure with baffles.

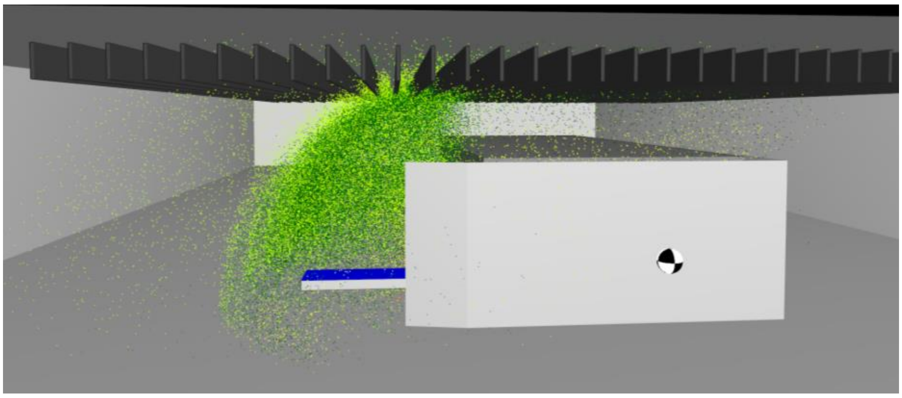

Figure 11: Absorbing baffle structure above the machine (each baffle modeled as separate absorbing object)

The calculation of the level at the work place results in 84 dB(A) for free field (fig. 9b), 89 dB(A) in the room (fig. 9c), 87 dB(A) with protecting screen (fig. 10a and b) and 85 dB(A) with absorbing ceiling (fig. 11).

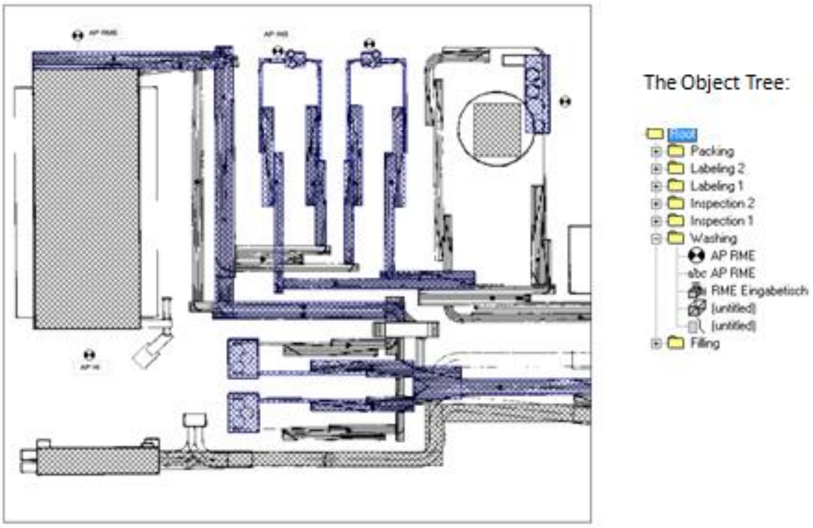

Figure 12: Modeling a complete plant applying the "Object Tree" to organize complex machines

The advantages of this software strategy become obvious if complete plants as shown in figure 12 are modeled. The data structure of each machine, once created and saved in a library, can be treated as one single element, integrated in the plant layout, transformed, duplicated or otherwise modified and adapted to the emission values L_{WA} and L_{pA} declared by the manufacturer or otherwise determined. The "Object Tree" is a data organization where all the elements a machine consists of are saved in one folder with the machines name and after calculation the level caused by each machine separately as well as the total level is listed for each work place. This structure facilitates the otherwise extremely time consuming development of necessary noise reduction measures to reach the defined target values, e. g. 85 dB(A) at the work places. Figures 13, 14 and 15 show the plant in 3D-presentation without treatment, with absorbing plane ceiling and with a baffle construction.

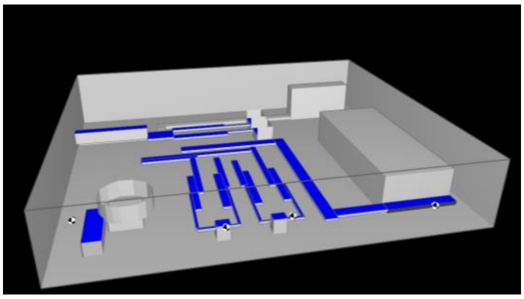

Figure 13: Model of the bottling plant without any treatment of room surfaces

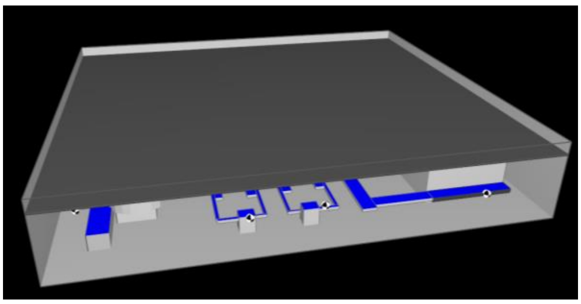

Figure 14: Model of the bottling plant with absorbing suspended ceiling

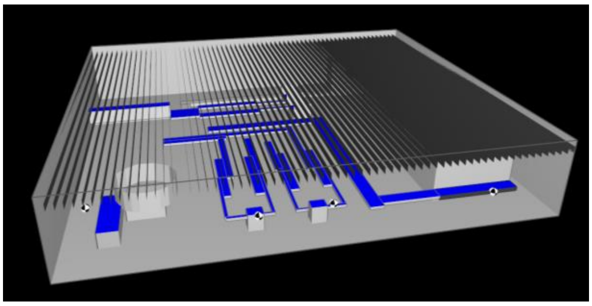

Figure 15: Model of the bottling plant with baffle system

4. Future Prospects

These few examples from bottling industry where shown to demonstrate the principles – it can be stated that the creation of virtual models of production plants and other facilities with work places where noise exposure may be an issue will become more and more a self-evident part of the planning process. The plant shown in the figure above is not only a simple 3D-pesentation of a CAD drawing – the machines, conveyors, pipes and other technical facilities are broken down and simplified to contain only those elements that are relevant for sound emission and propagation. Such a model is an excellent basis for all discussions about pros and cons of alternatively possible strategies to reach low noise exposures and allows minimizing the expenses necessary to reach certain target noise levels not to be exceeded.

It is obvious that the supplier of a certain type of machinery offers an optimal customer service if he provides a file with the acoustical 3D-model of his machine in the configuration as it is offered – this reduces the work to negotiate about noise issues to a minimum because the data file contains all the information – it is in a certain sense a very customer-oriented support and replaces any declaration and other formal procedures.

This software-based technique is not only a future oriented approach to create work places with minimized probability of hearing damage, but allows also to control other aspects of sound impact. An example is the planning of large open plan offices, where the layout shall be optimized to reduce the disturbance by other people speaking or vice versa where a good speech intelligibility between the members of a working group shall be ensured.

The acoustical 3D-model of the office – an example is shown in figure 16 – is simplified with respect to architectural aspects, but contains all information about the acoustic properties of furniture, suspended ceiling and other fittings.

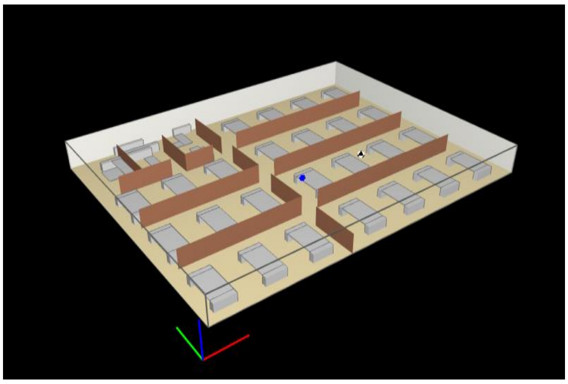

Figure 16: Acoustically oriented 3D-model of an extended office area

The partial screens subdividing the area into different sub-areas shall be arranged in a way that members of each working group can easily communicate but will not be disturbed by speech from other groups.

This can be controlled by determining approximately the STI (Speech Transmission Index) or other room acoustic parameters and to show up the area around a work place where this person speaking is well understood – the area inside the “Distraction distance” – and another zone outside the “Privacy distance” where understanding is not possible with high probability.

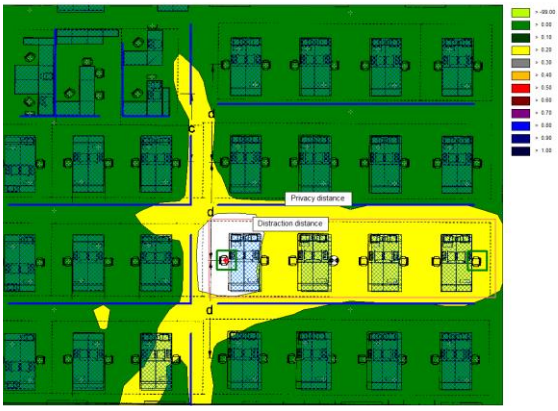

Figure 17: Distraction distance and Privacy distance around a work place based on the calculated STI

These methods will be improved step by step to become a self-evident part of the planning of working areas.

5. Annex validation of the calculation method

Many measurements have been performed the last decades to get reliable data applicable to check the accuracy of calculation methods.

One of these campaigns was to move a transportable screen to different environments inside empty and fitted industry halls and to measure the sound levels in different distances behind the screen if a dodecahedron loudspeaker produced sound with well defined emission in each frequency band at the opposite side. Figure 16 shows such an experimental setup in a retention basin with many sound scattering columns influencing sound propagation.

Figure 18: Measuring the screening effect with a transportable screen in a retention basin

In another campaign such a measurement of levels caused by the well defined source on receivers distributed along a straight line was performed in 122 industrial halls.

Measurement in a bottling plant

Resulting data set

Measurements have been made in 122 industrial halls (reverberation time and spatial sound decay in octave bands)

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 19: Measuring setup with dodecahedron and produced data – set for each of 122 halls

Figure 19 shows the measuring setup where the octave band spectra where measured along a straight line with the dodecahedron radiating with well known octave band sound power level. Additionally the reverberation time has been measured. The data set at the right side contains the geometric data of room and measuring positions, the sound power level of the source, the absorption coefficient of walls, ceiling and floor – applying a classification scheme developed in advance – the measured reverberation times and octave band spectra at the receiver positions and last not least an estimate of the density of scattering objects.

From each of these data sets a model was created – in an automated process – as it is shown in figure 20.

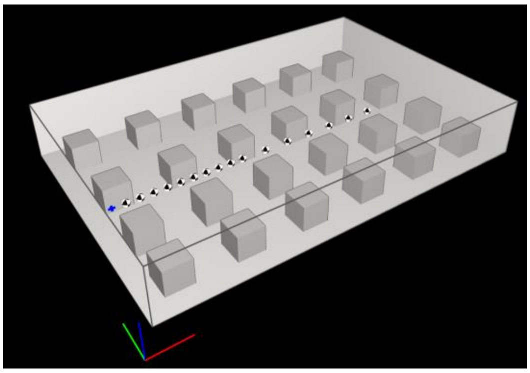

Figure 20: The model created automatically from the data shown right side in figure 19

The arrangement of scattering objects was determined from the above mentioned scattering density presuming a size of the objects typical for machinery. The octave band levels where calculated at each receiver position and subtracted of the measured ones taken from the data set.

Typical results for one industrial hall are shown with the diagrams in figures 21, 22 and 23, where the measured and the calculated levels in dependence of the distance from the source are shown. Figure 21 is based on the room complete empty and not fitted, figure 22 with an absorbing ceiling installed but otherwise empty, and figure 23 the same hall with absorbing ceiling and with the plant and machinery installed. It is obvious that the particle model applied to calculate sound propagation is well suited to reflect these different acoustic room properties.

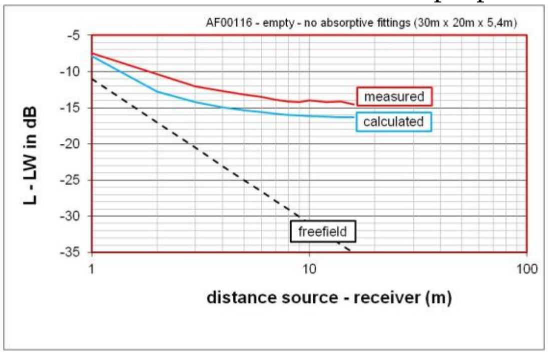

Figure 21: Comparison of calculated and measured levels with the room empty

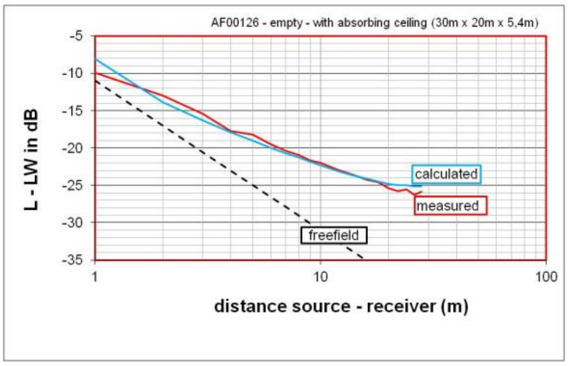

Figure 22: Comparison of calculated and measured levels with the room empty but with absorbing ceiling

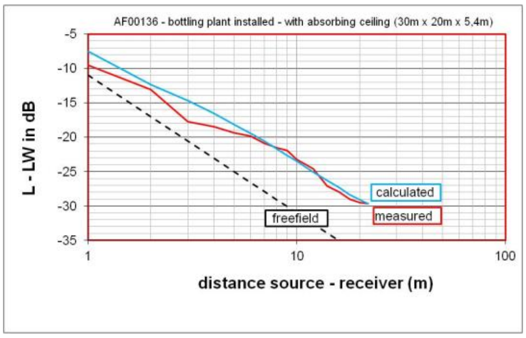

Figure 23: Comparison of calculated and measured levels with with absorbing ceiling and with machinery installed

Finally a statistical evaluation of level differences for all distances is shown in figure 24.

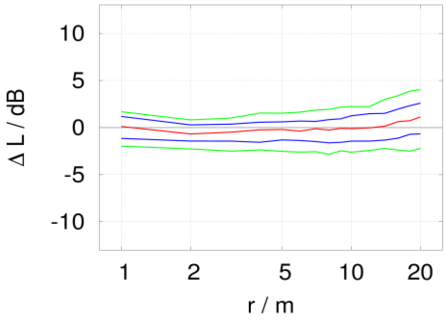

Figure 24: Statistics of level differences calculated – measured (Red – mean, blue – 50%, green – 80%)

This final result shows excellent agreement of calculated and measured levels – the mean value (red) is nearly zero and 50 % of all differences are smaller than ± 1 dB.

Therefore the particle-method applied is well suited to calculate sound propagation in closed room with technical installations.

References

[1] CadnaR – Prediction of Noise Levels inside Rooms (http://www.datakustik.com/en/products/cadnar/)

[2] ISO 3744: Acoustics – Determination of sound power levels and sound energy levels of noise sources using sound pressure – Engineering methods for an essentially free field over a reflecting plane

[3] ISO 11204: Acoustics – Noise emitted by machinery and equipment – Measurement of emission sound pressure levels at a work station and other specified positions applying accurate environmental corrections

[4] ISO 4871: Acoustics – Declaration and verification of noise emission values of machinery and equipment

[5] ISO 14257: Acoustics – Measurement and parametric description of spatial sound distribution curves in workrooms for evaluation of their acoustical performance

[6] ISO 354: Acoustics – Measurement of sound absorption in a reverberation room