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Theory and Applications of the Indoor Noise Module (VDI 3760)

The following Technical Note summarizes the mathematical concepts used in the SoundPLAN Indoor Factory Noise Module.

1. Basic Assumptions

The propagation model used in the Indoor Factory Noise Module is based on the VDI 3760 standard /1/. This standard makes the following assumptions:

- The laws of geometrical acoustics hold; wave phenomena are absent.
- Surfaces, which are all planar, reflect the sound energy spectrally as if from an infinite plane.
- Sound is treated as an energy function, not as a pressure function. Thus energies may be summed directly and phase effects are absent.
- Surfaces absorb sound energy according to an energy absorption coefficient, which is independent of the angle of incidence.

2. Background

Scattering of sound from obstacles in the room (tables, machines, shelves...) is statistically taken into account. Using the scattering object density (q) :

(1) $$q = \frac{S}{4V}$$

or the mean free path (l_m) of the sound rays between successive scattering objects

(2) $$I_m = \frac{1}{q} = \frac{4V}{S}$$

where

q	scattering object density [1/m]
l_m	mean free path length [m]
S	total surface of all objects located in the room with dimensions greater than the wavelength [m^2]
V	room volume [m^3]

The sound energy in the room consider the direct sound and the scattered sound. The direct sound is that part of the sound energy which has not been scattered on its way to the receiver. The direct sound energy of a point sound source in an infinite room, filled homogeneous with scattering objects, is defined in equation (3):

(3) $$E_d(r) = \left[\frac{P}{4\,\pi\,c\,r^2}\right] e^{-(q+m)\,r}$$

where

E_d	direct sound energy density [Ws/m^3]
P	sound power of the source [W]
c	speed of sound [m/s]
e	naperian base = 2.718..
r	distance between sound source and receiver [m]
m	air attenuation factor

The energy density of the direct sound in a closed room is the sum of the energy densities from the original and all mirror sources (reflected). For the mirror sources the reflection losses are to be taken into account.

In principal this sum is

$$E_d = \sum_{i=-\infty}^{+\infty} \sum_{j=-\infty}^{+\infty} \sum_{k=-\infty}^{+\infty} (1-\alpha_x)^{|i|}(1-\alpha_y)^{|j|}(1-\alpha_z)^{|k|} E_d(r_{(i,j,k)}) \tag{4}$$

where:

$\alpha_x, \alpha_y, \alpha_z$	mean absorption coefficients of opposite room boundary planes (mirror planes)
$r_{(i,j,k)}$	distance between mirror source and receiver
i, j, k	order of reflections over walls, ceiling and floor

The Indoor Factory Noise Module uses a ray tracing algorithm that scans the geometry in the x-y plane. The third dimension (z-direction) is considered by creating mirror sources based on the plane and horizontal floor and ceiling geometry. This model allows modelling of buildings with arbitrary floor plans, but flat and parallel floors and ceilings.

The following figures show the principal search and prediction method. Figure 1 shows the room geometry, the receiver and the sound sources. Figure 1 shows one search ray sent from the receiver, and its reflections. Mirror receivers are generated to trace the geometrical reflected ray. Figure 2 also shows the cross section and the registered sources, the mirror sources and the walls. Mirror sound sources are generated to account for the reflections from the ceiling and the floor.

The number of orders considered depend on the acoustical quality of the room. If the room is very reflective the required number of orders increases.

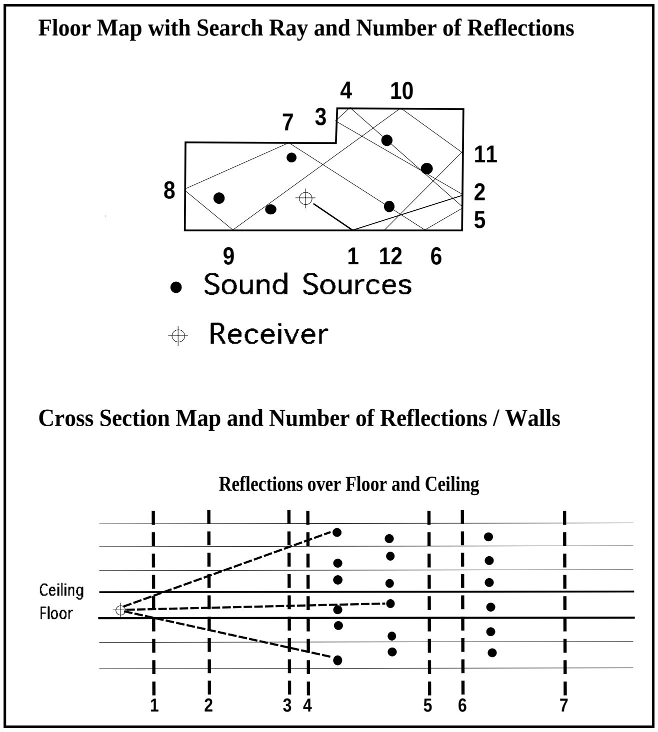

Figure 1,2 :Search and Prediction Method

3. Calculation of the Scattering Energy Density

The methodology used in the VDI 3760 is based on a 1986 document from S. Jovicic, based on his paper of 1979 (see reference /2/).

According to /2/ the energy density of the scattered sound in an infinitely wide flat room is:

(5) $$E_S(r) = \frac{3qP}{4\pi cr}\, e^{\left(-r\sqrt{3qa}\right)}$$

where

(6) $$a = b + \alpha_S' q + m$$

The mean absorption exponent of the scattering objects is

(7) $$\alpha_S' = -\ln(\alpha_S)$$

The exponent b describes the sound energy losses due to absorption of floor and ceiling. It is calculated as follows:

for qH<1

(8) $$b(\alpha) = -q \ln\left\{qH\left[\left(1-\frac{\alpha_i}{4}\right) - \left(1-\frac{\alpha_i}{2}\right)\frac{2}{\alpha'}\left[1-\exp\left(\frac{\alpha'}{2}\left(\frac{1}{qH}-1\right)\right)\right]\right]\right\}$$

for q H >=1

(9) $$b(\alpha) = -q \ln\left(1-\frac{\alpha_i}{4\,q\,H}\right)$$

(10) $$b = b(a_{floor}) + b(a_{ceiling})$$

where

H	mean height of the room
a_{floor} $a_{ceiling}$	mean absorption coefficient of floor and ceiling

The energy density in an infinite closed room is analogous to equation (4) and is defined as follows:

(11) $$E_S = \sum_{i=-\infty}^{+\infty}\sum_{j=-\infty}^{+\infty}\sum_{k=-\infty}^{+\infty}(1-\alpha_x)^{|i|}(1-\alpha_y)^{|i|}E_S(r_{(i,j,k)})$$

The reflection coefficients for floor and ceiling are omitted. Their effect is already considered in the derivation of equations (8) or (9).

4. Sound Propagation Curves

The Sound Propagation Curve (SPC) shows the acoustic "feedback" of the room. It is an indicator of the acoustical quality of the room itself, like the reverberation time (T_{60}).

The principal difference between the two indicators is :

1) T_{60} is characterizing the acoustical damping of the room over the time domain (time for a 60 dB decay)

2) SPC shows the sound reduction over the distance domain (drop off rate on measurement paths)

The dimensions of typical industrial rooms are disproportionate. The room dimension (length and width) are very large, compared to the room height. In these cases it is very difficult to measure the reverberation time and even to evaluate the acoustical quality of room based on Sabine's Theory. In contrast, the SPC shows the acoustical quality of the room along certain measurement paths.

The SPC measurement procedure uses a point source with a uniform sound radiation (e.g. omnidirectional loudspeaker system) and a known frequency pattern. The source is placed at the *beginning of the measurement path*. The sound pressure level is measured *along* the measurement path. Then the difference between sound power level and sound pressure level at a certain distance indicates the room feedback.

(12) $$D_{i,f}(r) = L_{p,i,f}(r) - L_{W,f,i}$$

Figure 3 shows a room with three measurement paths and the sound propagation curves obtained for those paths.

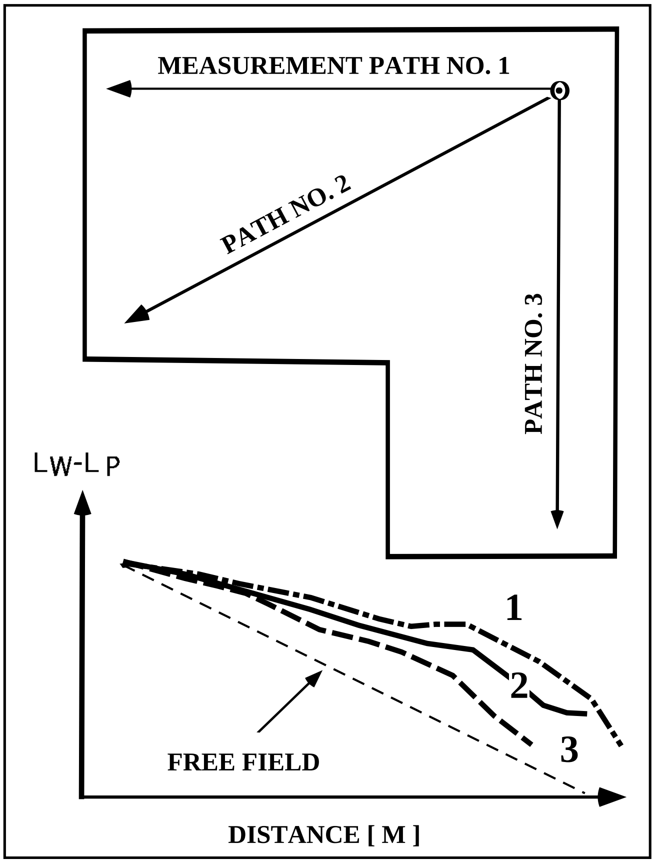

Figure 3 : Sound Propagation Curves for typical room

For the practical use of the SPC the results over 8 octave bands (63 to 8 kHz) are weighted based on a reference frequency spectrum for a typical sound source in this particular room. The weighting is considered as follows:

(13) $$D_i = 10\lg\frac{\sum_f 10^{(D_i+L_{W,f})/10}}{\sum_f 10^{L_{W,f}/10}}$$

The following table contains a normalized frequency pattern recommended in the VDI 3760. It is based on the frequency pattern of typical plant noise.

Table 1 : Normalized frequency pattern according VDI 3760

Frequency (Hz)	63	125	250	500	1000	2000	4 kHz	8 kHz
$L_{w,f,o}$ (dB)	-26.5	-22.1	-12	-6.4	-5.1	-5.7	-10.1	-15.1

Based on the SPC, it is possible to estimate the sound pressure level at a certain receiver location for a given set of sources.

For the assessment of the SPC, VDI 3760 reduces the data to two characteristics (see Figure 4):

1) the *Excess Level Above Freefield*
2) the *Decay per Doubling Distance*

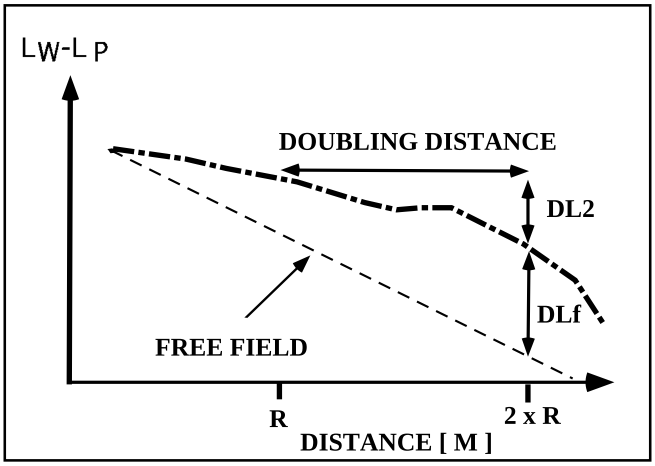

Figure 4 : Definition of SPC characteristics (DL2, DLf)

Both characteristics are calculated for three different distance ranges (near, middle and far).

(A) Near range $1\text{m} \le r \le 5$ m

In this range the SPC usually depends on the direct sound field of the sound source. The position of the source relative to reflecting surfaces (walls, floor and ceiling) and the absorption characteristics of these surfaces have a major effect on the sound propagation in the near field. In an ideal situation the dropoff rate is a near 6 dB.

(B) Middle range $5\text{ m} \le r\ 16$ m

This is the most important range for the acoustical assessment of a room. According to VDI 3760, this range should be used for the evaluation of the acoustical quality of a room.

(C) Far range $16\text{ m} \le r \le 64$ m

In the far range the SPC depends on the density of scattering objects in the room.

Excess level above freefield (DLf)

The freefield value $D_{i,B}$ for the distance r_i is defined by

(14) $$D_{i,B} = 20\log\left(\frac{r_o}{r_i}\right)\text{dB} - 11\text{dB}$$

where

$$r_o = 1\,\text{m}$$

The free field curve shows the ideal dropoff rate. The difference between the SPC and the free field curve is caused by the acoustical feedback of the room and scattering objects within the room. The smaller the DLf values, the better the acoustical quality of the room.

The difference level, DLf, between the free field curve and SPC at a distance i is

(15) $$DLf_i = D_i - D_{i,B}$$

For the evaluation of the excess level, the results are reduced to a single value for the three ranges. The mean excess level above freefield between r_n and r_m with the samples i= n..m is

(16) $$DLf(r_n, r_m, f) = \frac{\sum_{i=n+1}^{m}\left(DLf_i + DLf_{i-1}\right)\left(\log\frac{r_i}{r_{i-1}}\right)}{2\left(\log\frac{r_i}{r}\right)}$$

Decay per doubling of distance (DL2)

The decay per doubling of distance, or drop-off rate is the second room characteristic considered.

The decay, DL2, is calculated from the samples i = n..m of the SPC values D_i. The calculation in the frequency-band f uses a regression analyses:

(17) $$DL2(r_n, r_m, f) = -0.3\,\frac{z\sum_{i=n}^{m} D_i \log\frac{r_i}{r_o} - \sum_{i=n}^{m} D_i \sum_{i=n}^{m} \log\frac{r_i}{r_o}}{z\sum_{i=n}^{m}\left[\log\frac{r_i}{r_o}\right]^2 - \left[\sum_{i=n}^{m}\log\frac{r_i}{r_o}\right]^2}$$

where z = m - n + 1.

5. Indoor Noise Contour Maps

Along the calculation of sound pressure at particular receiver location and Sound Propagation Curves (SPC), SoundPLAN allows the calculation of noise contours. Calculations are made on a grid of receiver points and then contoured based on mathematical algorithms (Bezier).

Figure 5 shows typical results using the Indoor Factory Noise Module. Map 1 and 2 represent the sound pressure level in a steel plant before and after noise control measures are implemented. The measures included source noise control and the adding of an absorptive ceiling. Map 3 shows the noise reduction (difference level) achieved by the noise control measures.

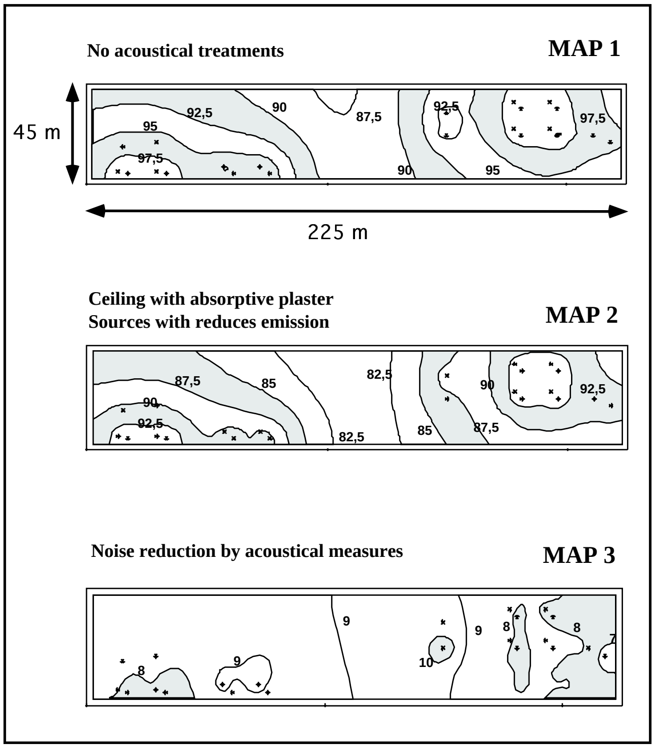

Figure 5 : Indoor Noise calculation in a steel plant

6. Practical Applications

The Indoor Factory Noise Module is ideal for the following cases:

- Predict noise exposure in an industrial room before the room is built
- Analytically evaluate the effect of different surface treatments (such as lay-in ceiling tiles or absorptive panels)
- Analytically evaluate effect of noise control for different sources in the room
- Predict new noise levels when equipment is added to or rearranged in a room
- Predict and map out 'low noise' areas to educate workers and reduce noise dose
- Do side by side comparison of competitive equipment with respect to the effect on room noise

References

/1/ VDI 3760 “Computation and measurement of sound propagation in workrooms”, 1994

/2/ S. Jovicic, “Calculation Guideline for the prediction of sound level in workrooms", Department of Labor, Health and Social Welfare of Nordrhein Westfalen (1979)