12 Simulation and auralization of airborne sound insulation

After dealing with virtual environments in examples of sound in free fields and in enclosures (room acoustics, Sect. 11.6), the variety of virtual worlds is now extended to situations with partition walls and to complete buildings. This field is classical acoustic engineering in buildings as part of architectural acoustics.

Building acoustics is the discipline of sound and vibration transmission in buildings. Unlike room acoustics, structural acoustics plays an important role in sound insulation. The models used are general models of structure-borne sound. The principles and methods discussed here can also be used in other fields such as vehicle acoustics or noise control, as will be seen.

A typical example of building acoustics is the problem of sound transmitted into a so-called "receiving room" from the room next door (source room), such as sound from a stereo set into the neighbouring sleeping room. Another example is impact noise created by walking on the floor in the room above, a typical example of a structure-borne source. Furthermore, sound generated by building service equipment such as heating or air conditioning systems is of interest. Noise from outside the building, such as traffic noise or industrial noise, involves the sound insulation of facades.

In typical room-to-room situations, the signal received sounds quiet (fortunately) and dull. An auralization must reproduce these properties (level and colouration) in the first place.

> Our goal in this chapter is to auralize the character of *sound transmission* between spaces separated by structures.

Specific spatial effects in the receiving room, such as early lateral fraction, are not relevant here. We will therefore focus on the basic quantities used in building acoustics today. From these quantities, strategies for designing auralization filters will be introduced. Sound reduction indices or standardized level differences will serve as input data for auralization. They may be obtained by calculation or by standard building acoustic testing. Standard building acoustics, thus, must be introduced in detail.

12.1 Definitions of airborne sound transmission

The basic quantity to describe the performance of construction elements[66] is the sound reduction index. It is defined as 10 times the logarithmic ratio of the incident sound intensity, I_0, and the transmitted intensity, I_t:

$$R = -10\log\tau = 10\log\frac{I_0}{I_t}, \tag{12.1}$$

where τ denotes the transmission coefficient, $\tau = I_t/I_0$.

In a free space with the partition separating two domains, R is identical to the sound pressure level difference, $D = L_S - L_R$. In buildings, however, the sound reduction index is related not to plane waves at one specific angle of incidence, but to diffuse and reverberant sound fields. From this fact, two consequences arise: a) the angle of incidence must be averaged and b) reverberation changes the level difference between the source and receiving room.

In the receiving room, the sound power, P, will create a diffuse sound field with energy density[67]

$$w_S = \frac{4P}{cA_S}, \tag{12.2}$$

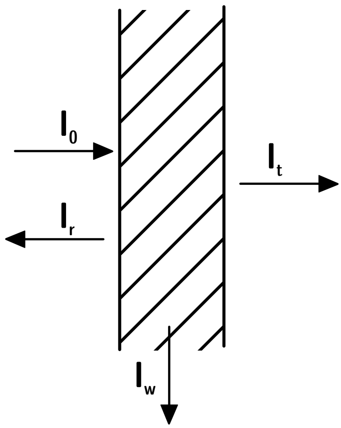

Fig. 12.1. Sound transmission through a wall

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[66] Construction elements are typically walls, floors, doors, windows, etc.

[67] The direct field is neglected; thus we assume a distance larger than the reverberation distance.

where A_S denotes the equivalent absorption area in the source room. The energy density will lead to an irradiation strength, B, of the partition wall. The irradiation strength is identical to the incident sound intensity, I_S, in the source room:

$$B = I_S = \frac{c}{4} w_S . \tag{12.3}$$

By definition, the sound reduction index is the ratio (in decibels) of the incident and the transmitted intensity. Thus, the power radiated from the partition walls is

$$P_R = S \cdot I_R = \frac{c A_R w_R}{4} . \tag{12.4}$$

From Eqs. (12.3) and (12.4), we can derive the sound reduction index, R, for two adjacent rooms with diffuse sound fields:

$$\begin{aligned} R = -10 \log \tau = 10 \log \frac{I_S}{I_R} &= 10 \log \frac{w_S}{w_R} + 10 \log \frac{S}{A_R} \\ &= L_S - L_R + 10 \log \frac{S}{A_R} \end{aligned} . \tag{12.5}$$

These definitions are most simple if the sound is transmitted via exactly one element, to which the transmission coefficient is addressed. In building practice, however, the situation is much more complicated. Sound and vibration and their coupling create energy transmission over multiple paths. Therefore, we must separate the problem into the elements involved. Building elements have finite size. They are coupled in s specific way, rigidly coupled or mounted with elastic connections. All these conditions have specific effects on the total sound insulation. Before we discuss the details of element coupling, we will study the basic effects of single partition sound transmission.

12.2 Sound insulation of building elements

Partition walls react to excitation by airborne sound waves. An adequate parameter to describe the amount of movement caused by sound pressure (or force) is wall impedance. Generally, the impedance may contain effects of inertia, of stiffness and of damping. Also, excitation and radiation depend on the size of the building element, as explained in Sect. 5.2.1.

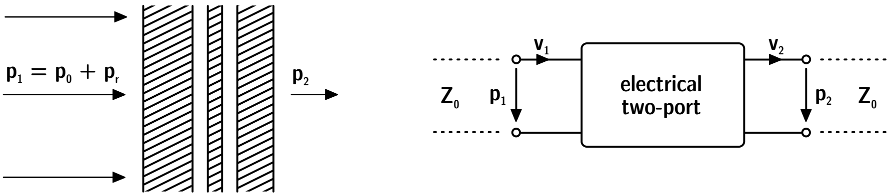

Fig. 12.2. Two-port model of partitions

A two-port model (Sect. 10.2) of the partition wall separating two domains, source side and receiving side, offers a very effective and illustrative study of basic effects. The partition wall is accounted for by its impedance, $\underline{Z}_p$.

The ratio of the transmitted pressure side to the sound pressure of the incident wave is

$$H_{\text{trans}} = \frac{p_0}{p_2} = \frac{1}{2}\left[a_{11} + a_{22} - \rho_0 c\, a_{21} - \frac{a_{12}}{\rho_0 c}\right], \tag{12.6}$$

where a_{ij} denotes the matrix elements of the two-port (see Sect. 10.2),

$$\underline{a} = \begin{pmatrix} \dfrac{p_1}{p_2} & \dfrac{\det \underline{Z}}{p_2 / v_1} \\ \dfrac{v_1}{p_2} & \dfrac{v_1}{v_2} \end{pmatrix}. \tag{12.7}$$

In this formulation, the sound reduction index of the partition is

$$R = 10 \log \left| H_{\text{trans}} \right|^2 . \tag{12.8}$$

Detailed information about the content of the two-port yields the matrix coefficients and the transmission function.

Single layers

With only an effect of inertia, the sound insulation of a single layer can be calculated easily. The impedance $\underline{Z}_p$ is given by $j\omega m''$, where m'' denotes the mass per unit area (see also Sect. 3.1.1). These results are, at least for buildings, a good estimate of the trend of insulation.

$$a_{11} = a_{22} = 1,\ a_{12} = -Z_p;\ a_{21} = 0, \tag{12.9}$$

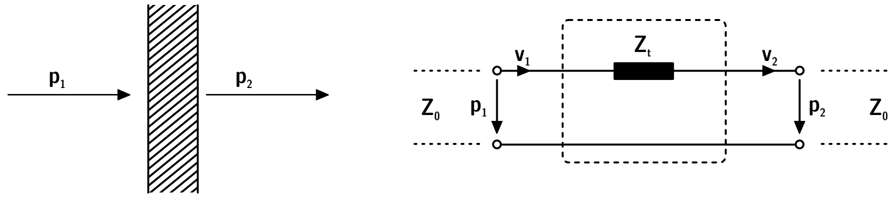

Fig. 12.3. Sound transmission through a partition with mass impedance

and according to Eq. (12.6)

$$R = 10\log\left|1 + \frac{Z_\mathrm{p}}{2\rho_0 c}\right|^2 \tag{12.10}$$

and

$$R = 10\log\left[1 + \left(\frac{\omega m''\cos\vartheta}{2\rho_0 c}\right)^2\right] \approx 20\log\left(\frac{\omega m''\cos\vartheta}{2\rho_0 c}\right), \tag{12.11}$$

the latter an approximation for $\omega m''\cos\vartheta \gg 2\rho_0 c$.

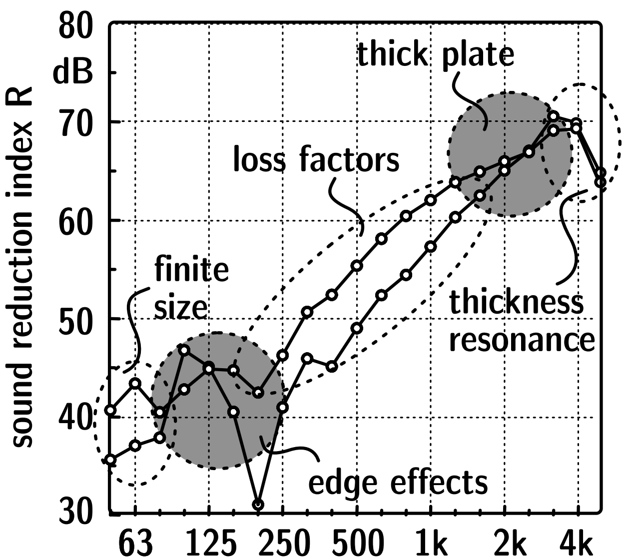

Fig. 12.4. Typical results of measured sound insulation of massive walls. Range of variation found in intercomparison tests (after (Meier 2000))

Stiffness effects such as bending waves (Sect. 5.2), size effects (Sect. 5.2.1) or losses (Sect. 5.2.2) are accounted for by adding more detailed terms into Z_p:

$$Z_\mathrm{P} = \mathrm{j}\left(\omega m'' - \frac{Bd\omega^3 \sin^4 \vartheta}{c^4}\right). \tag{12.12}$$

For an incident diffuse field, the effective sound reduction index is about 5 dB lower than the result of Eq. (12.11). The resulting sound reduction index is

$$R = 20\log\left(\frac{\omega m''}{2\rho_0 c}\right) - 10\log\left(\frac{1}{2\eta_{tot}}\sqrt{\frac{f_c}{f}}\right). \tag{12.13}$$

Double layers

The principle of the double wall is well known in lightweight constructions and for glazing. In many applications outside building acoustics, too, installation of a double or multiple wall system is an efficient way to improve the sound insulation at high frequencies. We come back to the two-port impedance model and extend the separation impedance to two mechanically decoupled masses. The inner part represents an air gap or a gap filled with viscoelastic material. The air gap as well as the material filling acts as a spring (Sect. 3.1.1, Eq. (3.13)).

For the frequency range above resonance ($\omega >> \omega_0$), the movement in the system (vibrational velocity) is concentrated in the first mass layer and the stiffness element. The stiffness element produces a short-circuit, so that the second mass stays at rest. The sound reduction index can thus be approximated by

$$R = 10\log\left(1 + \left(\frac{\omega(m''_1 + m''_2)\cos\vartheta}{2Z_0}\left(1 - \frac{f^2}{f_\mathrm{r}^2}\right)\right)^2\right). \tag{12.14}$$

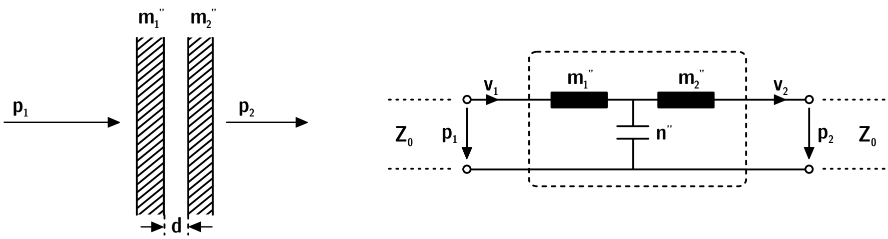

Fig. 12.5. Sound transmission through a double wall

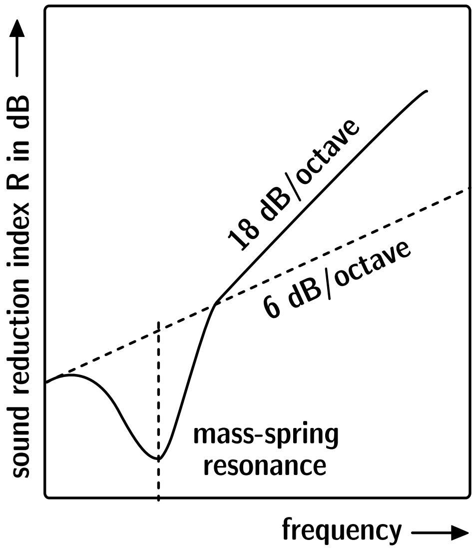

Fig. 12.6. Sound reduction index of a double wall

At frequencies less than the resonance frequency f_r, the spring shows an infinitely large impedance. The energy bypassing the masses is almost zero, and, thus, the behaviour of the double wall is identical to that of a single wall of mass $m''_1 + m''_2$. At resonance frequency, the separation impedance $Z_p = 0$ and accordingly $R = 0$. In practical cases, viscous losses in the air gap and friction in the mass layers limit the minimum of Z_p to a real value.

The resonance frequency is given by

$$f_r = \frac{1}{2\pi}\sqrt{\frac{1}{M''n''}}\,, \tag{12.15}$$

with the reduced mass M''

$$M'' = \frac{m''_1\, m''_2}{m''_1 + m''_2}\,. \tag{12.16}$$

12.3 Sound insulation of buildings

The most important difference between academic studies of sound insulation and the effective sound insulation in a real building is given by the presence of energy transmission via several paths. Particularly in the case of very high sound insulation of the separating wall, sound energy will flow significantly through other building components, such as small elements, doors, frames, flanking walls, suspended ceilings, access floors or facades.

As in a strong flood of water, any dam will be as efficient as the bypass water flow is prohibited. The characterization of sound energy flow, therefore, is not sufficiently covered by the incident and transmitted sound waves for adjacent rooms separated by the partition. Also the tangential energy flow in the structure or plates and beams involving all structural wave types, their interaction and transformation at junctions, and the structure-to-air radiation must be considered. Simulation and auralization in this kind of sound and vibration generation and transmission is a complex problem of transfer path identification and superposition.

The results are usually measured or predicted in one-third octave bands between 100 Hz and 3150 Hz, or in the extended range between 50 Hz and 5000 Hz. It is clear that the frequency range below 100 Hz may play a significant role in effective sound insulation, and this might even be increasing due to more low-frequency sound sources in residential buildings (TV and Hifi equipment).

By definition, the resulting sound reduction is denoted by R', the so-called “apparent sound reduction index”:

$$R' = -10\log\tau' = L_S - L_R + 10\log\frac{S}{A_R}, \tag{12.17}$$

where τ' denotes the apparent transmission coefficient, including all transmission paths. The reference to account for the sound transmission is still the partition wall with its surface area S, although the energy might be transmitted via flanking paths.

More elegant and more useful for auralization is the definition of sound level differences with reference to reverberation times in the receiving room, T_R, and standardization to $T_0 = 0.5$ s:

$$D_{nT} = L_S - L_R + 10\log\frac{T_R}{T_0}, \tag{12.18}$$

which is called the standardized sound level difference. The difference between R' and D_{nT} is a constant geometric term ($\approx V_R/3S$) introducing the receiving room volume, V_R:

$$D_{nT} = R' + 10\log\frac{0.32V_R}{S}. \tag{12.19}$$

Note that this equation allows predicting receiving room sound from source room sound and data from the transmission in the building structure. To achieve this form, we rewrite Eq. (12.19) as

$$L_R = L_S - D_{nT} + 10\log T_R + 3 \tag{12.20}$$

with all L and D in decibels and T in s. It will be used later in Sect. 12.5.

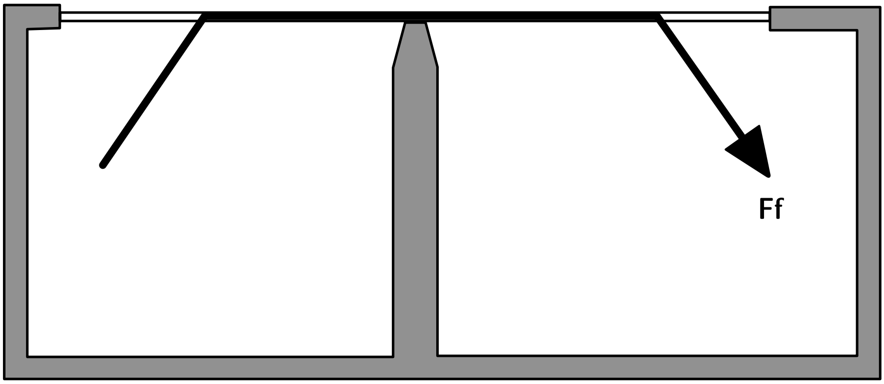

Fig. 12.7. Test facility for determining flanking transmission

12.3.1 Flanking transmission

The energy flow via flanking paths can be addressed similarly to direct sound transmission. The conditions for characterizing flanking paths are defined in measurement standards. Now, the direct path must be blocked and only one tangential energy path is active. Test facilities for flanking sound transmission are used to determine transmission coefficients for the specific energy flow considered, from the building element in the source room, *i*, to the element in the receiving room, *j*. Its definition, therefore, is equivalent to that of direct transmission:

$$R_{ij} = -10 \log \tau_{ij} = 10 \log \frac{P_i}{P_j} , \qquad (12.21)$$

where P_i and P_j denote the sound power incident on the element *i* in the source room and radiated by the element *j* in the receiving room, respectively.

The definitions and measurement procedures are specified for sound insulation test facilities. The energy flow in parts of the junctions is blocked by gaps, usually filled with resilient material. Hence the remaining energy transmission path can be controlled and studied with regard to the building constructions tested.

12.4 Sound transmission prediction models

To combine all relevant transmission paths, the specific transmission coefficients obtained in separated measurement conditions or calculated must be combined into a resulting sound transmission coefficient. This calculation consists of the addition of energy transmission with weighing factors proportional to the area of sound irradiation and radiation in the receiving room. Thus, it can be considered an energy balance approach between subsystems. In a consequent and theoretically valid approach, the statistical energy analysis, (SEA) is a method of interest. It required a high modal density and is, therefore, applicable in many building situations with low critical frequency, to allow SEA application in a wide frequency range (see also Sect. 10.1.2). In SEA, the energy flows between subsystems are calculated by using the energy losses in the systems and the corresponding coupling losses (coupling loss factors). "Systems" in the sense of the method are the statistical modal fields in the room cavities and on the plates (walls, ceilings).

The fundamental equations of the transmission model appropriate for sound insulation in buildings were developed by Gerretsen (1979). Although not explicitly referred to as the SEA approach, the equation system is equivalent to SEA, with the energy flow limited to cover transmission via the direct path and paths via one junction.

The total portion of the sound power transmitted is (see also Eq. (12.17))

$$\tau' = \sum_{i=1}^{N} \tau_i \tag{12.22}$$

with

$$\tau' = \tau_\mathrm{d} + \sum_{f=1}^{n} \tau_\mathrm{f}\,, \quad R' = -10\log\tau' \tag{12.23}$$

and

$$\tau_\mathrm{d} = \tau_\mathrm{Dd} + \sum_{F=1}^{n} \tau_\mathrm{Fd}\,, \quad \tau_\mathrm{f} = \tau_\mathrm{Df} + \tau_\mathrm{Ff}\,, \quad \tau_\mathrm{Dd} = 10^{-R_\mathrm{Dd}/10}\,. \tag{12.24}$$

Generally, all specific transmission coefficients are related to their corresponding flanking sound reduction indices, R_{ij}.

$$\tau_{ij} = 10^{-R_{ij}/10} \tag{12.25}$$

Accordingly they can be measured in test facilities. But the power reduction can also be calculated by summing the insulating effects of irradiation in the source room:

$$R_{ij} = -10\log\tau_{ij} = \frac{R_i}{2} + \Delta R_i + \frac{R_j}{2} + \Delta R_j + K_{ij} + 10\log\frac{S_S}{l_0 l_{ij}}\,. \tag{12.26}$$

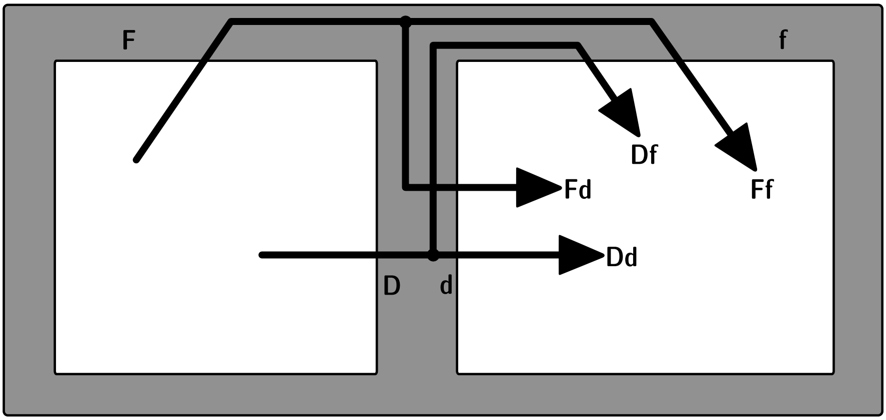

Fig. 12.8. Notation of flanking paths in sound transmission between rooms

In this formulation, reciprocity is used and, thus, the vibration level difference between the connected plates, i and j, are accounted for in a symmetric way and the result is combined. To derive this estimation of R_{ij}, the power flow balance is calculated between two adjacent rooms coupled by plates in L or T junction (Gerretsen 1979). The power transmitted over the junction is one of the crucial parts of the model. Thus, the vibration reduction index, K_{ij}, is specifically important. It describes the energy transmitted via functions of building elements. Its definition complies exactly with the energy balance equation used for airborne sound transmission (Eq. (12.17)),

$$K_{ij} = \frac{D_{v,ij} + D_{v,ji}}{2} + 10\log\frac{l_{ij}}{\sqrt{a_i a_j}}\,. \tag{12.27}$$

The latter term represents the total losses in the plates (see also Sect. 5.2.2). a is the equivalent absorption length of the plates' perimeters and l_{ij} the length of the common junctions in decaying sound fields in rooms, the equivalent absorption length can be related to the decay time, here called structural reverberation time. The relationship between the equivalent absorption length, a, and decay of vibration energy, T_{s}, in a plate of area S is

$$a = \frac{2.2\pi^2 S}{cT_{\mathrm{s}}}\sqrt{\frac{1\mathrm{kHz}}{f}}\,. \tag{12.28}$$

Finally, the structural reverberation and the loss factor can be separated into three parts, according to the basic information in Sect. 5.2.2. In the application discussed here, sound insulation in building structures, all loss effects are relevant, depending on the construction material. It is well known in building construction that losses may play a significant role in enhancing sound insulation, and this can be achieved either by internal material losses or by energy flow over junctions away from the receiving room (equivalent to grounding electric current).

The final adjustment of absorption must be done with respect to the actual energy flow in the field situation. This procedure is necessary in case of laboratory data of a and T_s under certain boundary conditions, while the mounting method or connection between building elements in the real building might be different.

12.5 Auralization of airborne sound insulation

Before discussing the procedure for creating an auralization filter, we separate the problem into the possible variants of source signal recording. The interface between the source signal and the filter must be defined accordingly. The source can either be recorded in the source room, thus containing the source room's reverberation, or it can be recorded in a free field. In the latter case, the directivity in notation of a polar pattern or as coded data can also be taken into account.

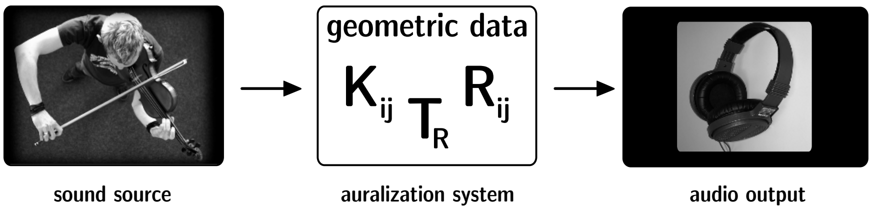

Fig 12.9. From input data to sound: Auralization of buildings

Source signal recording in the source room

Starting with the input data of sound insulation in frequency bands which stem from prediction or from measurement, we can create auralization filters. A prerequisite, however, is that the transmission paths are clearly separated and that the significant contributions are captured in the model. Based on the calculation of the effective sound insulation, including all relevant transmission paths (Eq. (12.22)), the sound level reduction for each path is obtained. Since the energy model is using the fact that we have statistical modes and energy summation, it is easily transferred into software. The resulting standardized sound level difference, D_{nT}, is

$$\begin{aligned} D_{\mathrm{nT}} &= L_{\mathrm{S}} - L_{\mathrm{R}} + 10\log\frac{T}{0.5\ \mathrm{s}} \\ &= -10\log\tau' + 10\log\frac{0.32\,V}{S} = -10\log\tau_{\mathrm{nT}} \end{aligned}, \tag{12.29}$$

where V denotes the receiving room volume in m^3 and S the wall surface of the partitions in m^2.

The clue for getting from simulation to auralization is, again, mapping the problem onto a problem of signal processing. By introducing the sound pressure signals, p_S and p_R, in the source room and the receiving room, respectively, we rearrange Eq. (12.29) as

$$p_{\mathrm{R}}^2 = p_{\mathrm{S}}^2\,\frac{\tau_{\mathrm{nT}}\,T}{0.5\ \mathrm{s}} \tag{12.30}$$

and

$$\begin{aligned} p_{\mathrm{R}}(\omega) &= p_{\mathrm{S}}(\omega)\cdot F_{\mathrm{total}}(\omega) \\ &= p_{\mathrm{S}}(\omega)\sum_{i=1}^{N} F_{\tau,i}(\omega)e^{-j\omega\Delta\tau_i}F_{\mathrm{rev},i}(\omega) \end{aligned}, \tag{12.31}$$

where $F_{\tau,i}$ denote interpolated filters which are obtained from the energy transfer spectra of the paths involved. $\Delta\tau_i$ are delays corresponding to the geometric situation of the walls and the observation point. $F_{rev,i}$ is the reverberation excited by each of the sound transmitting elements in the receiving room. The absolute sound pressure level in the receiving room is

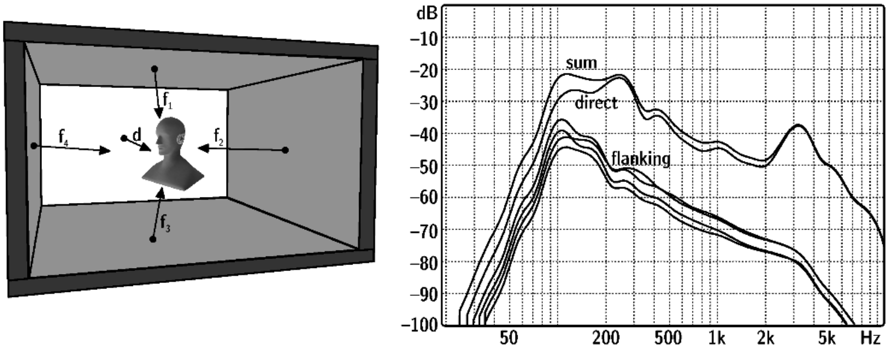

Fig. 12.10. Geometric situation and interpolated filters of the sound transmission paths involved

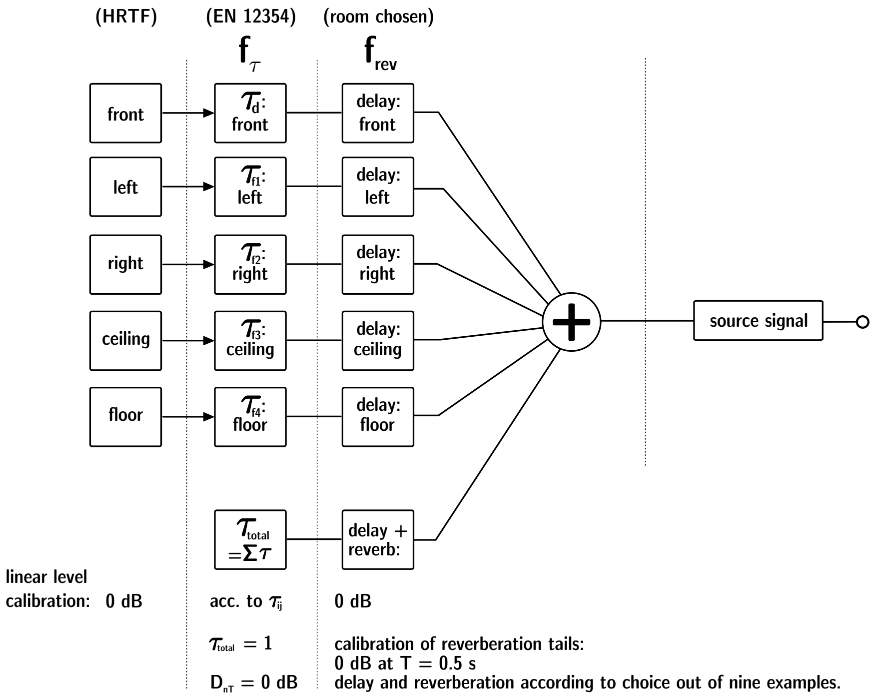

Fig. 12.11. Flow chart for auralization of airborne sound insulation

correct if the input sound pressure signal in the source room is calibrated with reference to $2 \cdot 0^{-5}$ Pa. Note that $p_S(\omega)$ is nothing but the complex spectrum of the recorded source time signal. Equation (12.31) can hence be expressed in the time domain by

$$p_R(t) = p_S(t) * f_{\text{total}}(t)\,, \tag{12.32}$$

where f_{total}(t) denotes the transmission impulse response; see Fig. 12.12.

Except for the phases, the total set of transfer functions is represented quite accurately, as long as the frequency interpolation does not smooth the exact physical behaviour too much.[68] This situation is acceptable since phases in reverberant sound fields cannot be recognised by human hearing. This does not apply, however, for the discrimination of direct sound and the first (early) reflections related to the direction of sound incidence and the spatial aspects of the early part of the impulse response. Those phases are well covered by $\Delta\tau_i$.

[68] If the interpolation would be too rough, statistical energy analysis would not be an appropriate model. Thus, the model has its limits at low frequencies (at low modal densities).

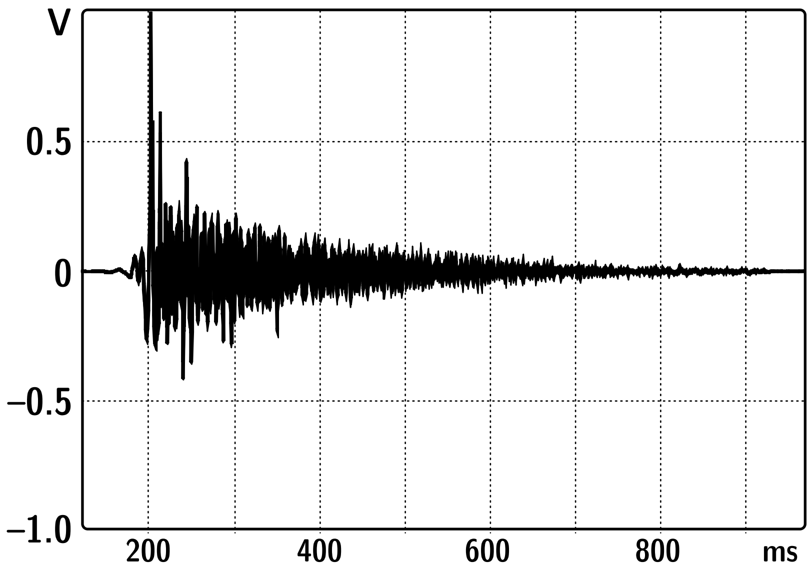

Fig. 12.12. Impulse response of the transmission source room–receiving room

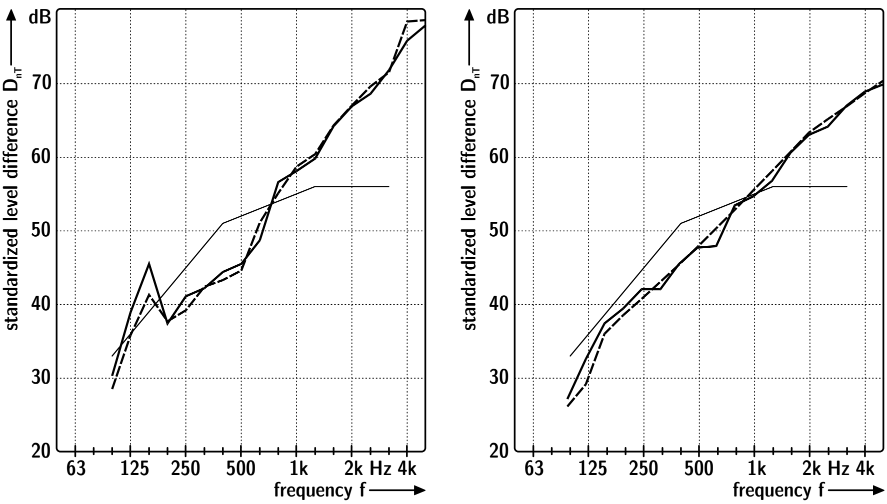

Fig. 12.13. Comparison of the input data of D_{nT} and D_{nT} measured from the auralized signals. The auralization stimuli were created by using pink noise and a measurement by feeding the signals to headphones on an artificial ear

The deviation of the auralized level differences from the measured level differences is mostly less than 1 dB. A deviation of more than 2 dB occurs only at low frequencies. These uncertainties are acceptable since they occur anyway in measurements at these low frequencies due to modal effects. For the auralization "measurement," only one point in the receiving room was used. With appropriate spatial averaging, the agreement would be even better.

Source signal recording in free field

In the examples described in the section above, it is assumed that reverberation affects the result primarily in the receiving room. This approach is inherently consistent since the auralization filter of that kind was related to the source room level, thus including the source room reverberation. The source room, however, may also contribute to the listening experience by its reverberation, as pointed out by Rindel (2006). An extension in this respect is implemented into the model by using the sound power, P, of the source as a reference instead of the source room level.

With reference to the sound power of the source, L_w, the fundamental equation of sound insulation auralization reads (see also Eq. (4.39))

$$D_{nT} = L_w - L_R + 10\log T_S + 10\log T_R - 10\log V_S + 17\,, \tag{12.33}$$

where $D_{nT} = -10\log \tau_{nT}$ denotes the standardized sound level difference, L_w the sound source power, L_R the receiving room sound pressure level, T_S and T_R the reverberation times of the source room and the receiving room, respectively, and V_S the volume of the source room.

In energetic notation and rearranging to obtain the sound pressure in the receiving room, this reads

$$p_R^2 = \left(2.0 \cdot 10^4 \, \frac{\text{Pa}}{\text{s}}\right) \cdot P \cdot \frac{\tau_{nT}\, T_S T_R}{V_S}\,. \tag{12.34}$$

As expected, the sound power of the source determines the squared sound pressure level in the receiving room. The factor $2 \cdot 10^4$ Pa/s stems from combination of various constants such as the reference level for sound pressure ($p_0 = 2 \cdot 10^{-5}$ Pa), the reference sound power level ($P_0 = 10^{-12}$ W) and from the reference reverberation time ($T_0 = 0.5$ s) in the definition of D_{nT}.

Equation (12.34), however, is not applicable straightforwardly to creating a source-filter model, since the source pressure is somehow hidden in the sound power. For source characterization, however, the far-field pressure in a well-defined direction and distance and the directivity pattern can be used (see Sect. 8.1). Omnidirectional sources and signals recorded in a free field at 1 m distance yield[69]

$$p_R^2(\omega) = \left(2.0 \cdot 10^4 \, \frac{\text{Pa}}{\text{s}}\right) \frac{4\pi}{\rho_0 c} \cdot p_S^2(\omega)\Big|_{1\text{m}} \cdot \frac{T_S T_R \tau_{nT}}{V_S}\,, \tag{12.35}$$

[69] All quantities are to be expressed by using their numerical values in SI units.

which can further be expanded into

$$
\begin{aligned}
p_{\mathrm{R}}(\omega) &= p_{\mathrm{S}}(\omega)\big|_{1\mathrm{m}} \cdot 24.6 \cdot \sqrt{\frac{T_S T_{\mathrm{R}} \tau_{nT}}{V_{\mathrm{S}}}} \\
&= p_{\mathrm{S}}(\omega)\big|_{1\mathrm{m}} \cdot F'_{\mathrm{total}}(\omega) \\
&= p_{\mathrm{S}}(\omega)\big|_{1\mathrm{m}} \cdot \frac{24.6}{\sqrt{V_{\mathrm{S}}}} \cdot F_{\mathrm{rev,S}}(\omega) \cdot \sum_{i=1}^{N} F_{\tau,i}(\omega) e^{-j\omega\Delta t_i} \cdot F_{\mathrm{rev},i,\mathrm{R}}(\omega)
\end{aligned} \quad . \tag{12.36}
$$

The filters to be created in this situation must be related to a free-field calibrated sound source, $p_{\mathrm{S}}(\omega)|_{1\mathrm{m}}$[70], to a reverberation filter, obtained by simulation or measurement in the source room, $F_{\mathrm{rev,S}}$, reverberation determination by simulation or measurement in the receiving room, $F_{\mathrm{rev},i,\mathrm{R}}$, and to the standardized sound insulation quantity D_{nT}, as described above. The reverberation time filters must be calibrated with regard to a total energy of 1 when $T = 1$ s, respectively. As above, the same can be expressed in the time domain by

$$p_R(t) = p_S(t)\big|_{1\mathrm{m}} * f'_{\mathrm{total}}(t) , \tag{12.37}$$

with $f'_{\mathrm{total}}(t)$ denoting the transmission impulse response.

In contrast to the example of source recording in the source room, a directional source must be treated in a specific way. The direction used in the recording situation must match the directional reference in the determination of the source room impulse response or the corresponding transfer function, $F_{\mathrm{rev,\,S}}(\omega)$. This situation can be understood by considering the differences in the intensities radiated in various directions into the source room. This process feeds the source room reverberation with distributed sound with a total power of $P\ |\Gamma|^2$, which can also be introduced in Eq. (12.34).

The methods described in this chapter are explained with the example of airborne sound transmission in buildings. Nevertheless, they are applicable to equivalent problems of transmission paths between two cavities or enclosures. Such applications might be airborne sound transmission in vehicles, in ships or similar cases in noise control engineering; see Chap. 14.

[70] Note the different reference for the recorded signal compared with Eq. (12.31).