Chapter 3

Building Acoustics

3.1 FOREWORD

When an incident sound wave arrives onto a material, part of it can be:

- Reflected
- Transmitted through the material
- Absorbed inside the material

This leads to the definition of:

- A reflection coefficient $\rho$ defined as the ratio of reflected energy over incident energy
- A transmission coefficient $\tau$ defined as the ratio of transmitted energy over incident energy
- An absorption coefficient $\alpha$ defined as the ratio of reflected energy over incident energy

$$\rho^2 + \tau^2 + \alpha^2 = 1$$

One may care to note that those coefficients are frequency dependent. Usually the higher the frequency, the lower the transmission coefficient. More to the point, usually with soft or porous materials, the higher the frequency, the higher the absorption coefficient.

3.2 INTRODUCTION

As implied by its name, the field of building acoustics covers all aspects involved in the construction of a building. Usually such acoustics mainly revolve around a same concern: enabling the occupants to be decently protected from the noise and vibration aggressions from the outside environment, ensuring proper sound insulation between the various spaces of the building, controlling the reverberation inside the premises, and controlling the noise from mechanical equipment. In addition, one will also be concerned with the noise radiated to the environment either from the mechanical equipment or from the activities carried out inside the building.

This chapter is devoted to the basic physics of those phenomena. Application of those bases will be done in the relevant following chapters.
3.3 SOUND INSULATION

3.3.1 Experiencing Sound Insulation

Whoever has been living in flats certainly has firsthand experience in the notion of sound insulation when woken up in the middle of the night by noise from the next door flat! One may even have observed that according to the nature of the walls and the dimensions of the room, the perceived sound insulation was different.

3.3.2 Sound Reduction Index

The sound reduction index of a wall or floor is measured in a laboratory that features heavy slabs and walls with a framed 10 m² opening in the middle. Due to the constitution of the envelope of the measuring rooms that are separated by an expansion joint, flanking transmissions can be considered negligible, and the sole contribution to the sound levels measured in the receiving room comes from the radiation of the floor or wall under test. The floor or wall under test is excited using a diffuse sound field that is generated using a couple of loudspeakers located in one room (labeled “emission room”) and directed toward the corners of the room opposite of the wall under test; the mean sound pressure level is measured in both the emission room and the receiving room.

The sound reduction index \( R \) is given by

\[
R = L_1 - L_2 + 10 \log \left( \frac{S}{A} \right)
\]

where \( L_1 \) is the mean sound pressure level in the emission room, expressed in dB, \( L_2 \) is the mean sound pressure level in the reception room, expressed in dB, \( S \) is the area of the floor or wall specimen under test, expressed in m², and \( A \) is the equivalent absorptive area in the reception room, expressed in m².

Measurements are performed either in the 100–3150 Hz range (ISO) [1] or in the 125–4000 Hz range (ASTM) [2]. More recently, EN/ISO standards have attempted to extend the range in the low-frequency region [3] down to the 50 Hz third octave band.

Of course, the measurement of the sound reduction index of a building component must be performed under laboratory conditions. But it may be possible to perform such a measurement \textit{in situ} using sound intensity measurements as long as some conditions are met (mainly a low and stable background noise, and either a nonreverberant environment on the receiving side or reflective walls at least 3 m from the element under investigation) [4].

Note: When performing a sound reduction index measurement on a wall, roof, or floor sample, bear in mind that the dimensions of the sample should be as close as possible to the dimensions used in the project. Using smaller dimensions will usually result in overestimating the performance in the low-frequency range.

3.3.3 Sound Reduction Improvement Index

The addition of a doubling on an existing wall or floor will, of course, have consequences on the value of the sound reduction index. The effect of a doubling is characterized by the sound reduction improvement index \( \Delta R \). The value of \( \Delta R \) is obtained through the measurement of the sound reduction index of the main wall, and the measurement of the sound reduction index of that wall with its doubling:

\[
\Delta R = R_{\text{wall with doubling}} - R_{\text{wall alone}}
\]
Of course, the lighter the wall, the larger the value of \( \Delta R \) will be. In addition, the more porous the wall, the larger the value of \( \Delta R \) will be. The usual walls used for a test are a 16 cm plain concrete wall, a 20 cm brick wall, and a 20 cm hollow concrete block wall. Plaster blocks 7 cm thick may also be found (e.g., [82]).

Please do note that the sound reduction improvement index \( \Delta R \) can feature a negative value (i.e., \(-4 \) to \(-7 \) dB) for a plasterboard on polystyrene doubling glued on a brick wall. Whenever using a doubling, one must make sure that it will not hamper the overall sound reduction performance of the wall construction under consideration.

### 3.3.4 Sound Insulation

The sound insulation between two rooms will depend not only on the direct transmission through the separating wall or floor, but also on the flanking transmissions by all walls or floors linked to this separating element. Last, parasite transmissions (such as leakage around a constructive element or through a duct or opening) will also play a role. Figure 3.1 displays a few transmission paths between two rooms.

The sound insulation between rooms usually is measured using a diffuse sound field that is generated using a couple of loudspeakers located in one room (labeled “emission room”); the mean sound pressure level is measured in both the emission room and the receiving room.

The sound level difference \( D \) is given by

\[
D = L_1 - L_2
\]

where \( L_1 \) is the mean sound pressure level in the emission room, expressed in dB, and \( L_2 \) is the mean sound pressure level in the reception room, expressed in dB.

However, this sound insulation value is sensitive to the amount of acoustic absorption inside the receiving room: This would eventually mean that according to the fittings in the room, one would pass or fail the sound insulation criteria. In order to avoid this inconvenience, the usual rule is to standardize the result by the reverberation time.

The standardized sound insulation \( D_{nT} \) is given by

\[
D_{nT} = L_1 - L_2 + 10 \log \left( \frac{T}{T_0} \right)
\]

where \( L_1 \) is the mean sound pressure level in the emission room, expressed in dB, \( L_2 \) is the mean sound pressure level in the reception room, expressed in dB, \( T \) is the reverberation time.

![Figure 3.1 Direct and flanking transmission between rooms.](image-url)
time in the receiving room, expressed in s, and $T_0$ is the reference reverberation time (usually 0.5 s).

For many years the usual frequency measurement range used to be 100–3150 Hz (ISO) [5] or 125–4000 Hz (ASTM) [6], with some other countries using the 100–5000 Hz (e.g., France [7]). More recently, EN/ISO standards have attempted to extend the range in the low-frequency region up to the 50 Hz third octave band.

**Note:** The choice of frequency range is not a purely academic matter; limiting the higher-frequency value will often result in avoiding the presence of a badly located coincidence frequency in the expression of the result, and influence the final single number rating (cf. Section 3.5).

While inside a building space the preferred method will be to use a loudspeaker turned toward a corner to help generate as close as possible a diffuse field; when attempting to measure the sound insulation of the façade things get more complicated: One is no longer in diffuse field conditions, and the choice is between using a loudspeaker sound source or the actual traffic noise [9]. Due to the coincidence effects, one has to carefully locate the sound source according to the standard recommendations (incidentally, make sure both the neighbors and the police are forewarned of the measurement too!).

**Note:** A construction project very often features a proof room that will show to the architect and the end user how the room will look. When required, in time it can be used for acoustic testing purposes too, but kindly remember that any leakage in the envelope of this proof room will result in unsatisfactory acoustic performance, and the contractor must be made aware of it.

Figure 3.2 displays the effect on the sound field of a room when a window is slightly opened or leaky.

### 3.3.5 Single Number Rating

In order to help speed up the rating of partition or floor assemblies, one usually relies on a so-called single number rating. This is an obvious simplification, as instead of working on the usual six octave bands (125–4000 Hz) of building acoustics, one now uses a single value. Now for the bad news: Nearly every organization has its own system. To try to simplify things, the American Society for Testing and Materials (ASTM) uses the Sound Transmission Class (STC) [10], which features a sliding contour. This contour runs 9 dB per octave from 125 to 500 Hz, 3 dB per octave from 500 to 1250 Hz, and stays flat from 1250 to 4000 Hz. One glides the contour over the sound reduction or sound insulation...
curve tested until the sum of negative deviations is no greater than 32 dB and the maximum negative deviation is 8 dB. ISO uses the $R_w$ or $D_w$ system \[11\], which is nearly identical, save that the starting point is at 100 Hz and the endpoint at 3150 Hz. In order to cope with European regulations, there usually are two values between parentheses next to it that are respectively given the symbols $C$ and $C_t$, in order to obtain the value expressed for a pink noise and a traffic noise, respectively. So, when the sound reduction index value of a window is announced using a single number, one had better make sure of the nature of the indicator used.

The reader has understood by now that according to the spectrum emitted the sound source used for the tests, the single number rating value will not be the same. Some European countries (e.g., France and Spain) favor a traffic noise for the expression of façade sound insulation results, and the numerical value typically is 3 to 7 dB lower than the corresponding $R_w$ value (see Section 3.12.6).

In order to cope with low frequencies down to 50 Hz, ISO has extended its $R_w$ contour, with the relevant definition in standard ISO 16717-1 \[12\].

Note: Do be careful when dealing with a single number rating, as its value will depend on its definition (cf. Section 3.12.6).

### 3.3.6 Computing the Sound Reduction Index and the Sound Insulation

#### 3.3.6.1 Sound Reduction Index

The crudest model is known as mass law. The sound reduction index $R$ for a single wall is given by

$$R = 20 \log(mf) - 48$$

where $m$ is the mass per area unit of the wall or floor, expressed in kg/m², and $f$ is the frequency, expressed in Hz.

There are a few computer programs available to try to compute the sound reduction index of a wall or a floor \[13, 14\]. Usually such programs rely on the mass law but also quite often on a reasonable database to help tune the relevant parameters.

When dealing with multiple layers (e.g., a massive wall with a glued doubling made of a mineral wool factory assembled on plasterboard) or with multiple walls, there will be a resonance appearing for the gap between the plates. From this resonance frequency, the acoustic performance is much better (e.g., 12 dB per octave for a double wall) until dips from coincidence effects appear. More to the point, the type of connection between leaves of the wall will play a significant role (see Section 3.12.8). Usually, a multiple wall will fare much better than a single wall in the medium- and high-frequency range, but it can also come out the loser in the lower-frequency range.

A word of advice there: Whenever one tries to assess the sound reduction index of a wall or floor, first try to compute the sound reduction index of a known construction that was subjected to a laboratory test. Only then will you be able to try to start changing such parameters as mass and stiffness. Change one parameter at a time to check its influence. Do not hesitate to wonder and ask questions (e.g., it is not unusual on some computation models to observe a significant sound reduction index value increase when adding mineral wool on one side of a single wall; you know, of course, that it is ridiculous and does not happen in the real world!).
3.3.6.2 Sound Insulation

There are a few computer programs available to try to compute the sound insulation between rooms [15]. Such programs rely on the knowledge of the sound reduction index of the various walls, as well as their coupling parameters, and operate according to ISO 12354 [16]. Most of the time they come with a rather significant database.

A word of advice there: Should one of the constructive elements be missing from the database, whenever possible proceed as with the previous chapter, using as a basis as close as possible a material to try to get plausible coupling factors.

Looking at the results, one may try to modify one parameter at a time (e.g., increase the performance of the separating wall or floor) in order to check its influence. Usually the results can be displayed graphically so one may pinpoint which component needs upgrading.

While such computer programs are now quite user-friendly and reliable when it comes to concrete construction and dimensions similar to those encountered in dwellings, they can get trickier and more prone to errors when it comes to light construction or wood construction, or larger dimensions. There are currently developments in this field to try to cover wood constructions that are quite fashionable nowadays [17].

3.3.7 Noise Radiated by a Construction

The noise radiated by a building will of course depend on the sound reduction index of each envelope component as well as its respective area.

The sound power level $L_w$ radiated by a component of area $S$ and sound reduction index $R$ is given by [18]

$$L_w = L_p - 3 - R + 10 \log(S)$$

where $L_p$ is the sound pressure level inside the building.

There are a few things to get from this formula: To start with, large elements with a rather small sound reduction index value (e.g., the metal roof of a building) will be major contributors. So will the apertures (that can be considered an element with $R = 0$) and weaknesses with regards to other components.

3.3.8 Standards and Regulations

For a long time, there were various ways of expressing the acoustic requirements for buildings, especially dwellings, and a rather broad range of values to go with it [19, 20]. Nowadays, there are quite a number of standards and regulations pertaining to sound exposure levels and sound insulation [21, 22]. A few of them are given in the various chapters of this book regarding the main types of constructions. Typically, one may care to note the following constraints:

- There are limits, expressed as noise levels, regarding the noise exposure of workers (e.g., [23]), or the danger limit for people exposed to high-level music (e.g., [24]).
- There often are minimum sound insulation values required for specific types of construction, such as dwellings, schools, hospitals, etc. (e.g., [20, 21, 24–39]).

3.4 IMPACT NOISE

3.4.1 Experiencing Impact Noise and Walking Noise

Everyone probably has experience in the notion of impact sound transmission when woken up by the heavy steps of the occupant upstairs or simply by the steps of someone in another
room within the same flat. One may even have observed that according to the nature of the
floor, the walls, and the dimensions of the room, the perceived impact noise was different.
One has probably also observed that according to the nature of the floor covering or floor
constitution, the noise of the steps inside the room where one is walking may sound quite
differently (e.g., a wooden floor on joists will sound more hollow than a plain concrete floor).

3.4.2 Impact Noise of a Floor

The impact noise of a floor is measured in a laboratory that features a heavy slab with a
framed 10 m² opening in the middle. Due to the constitution of the walls, flanking transmis-
sions can be considered negligible, and the sole contribution to the sound levels measured in
the receiving room comes from the radiation of the test floor. The floor under test is excited
using an impact machine (also designated the tapping machine).

The impact noise \( L_n \) is given by

\[
L_n = L_1 + 10 \log \left( \frac{S}{A} \right)
\]

where \( L_1 \) is the mean sound pressure level in the reception room, expressed in dB, \( S \) is the
area of the floor specimen under test, expressed in m², and \( A \) is the equivalent absorptive
area in the reception room, expressed in m².

The standard describing the measurement procedure is usually ISO 140-6 [40] or ASTM
E492 [41]. Those standards typically consider either the 100–3150 Hz range (ISO) or the
125–4000 Hz range (ASTM). More recently, EN/ISO standards have attempted to extend
the range in the low-frequency region [42] down to the 50 Hz third octave band.

3.4.3 Impact Noise Transmission

The impact noise transmitted into a room will depend not only on the direct transmission
through the separating floor, but also on the flanking transmissions by all walls linked to
this separating element. Last parasite transmissions (such as leakage around a constructive
element or through a duct or opening) will also pollute the result.

The impact noise transmitted into a room usually is measured using an impact machine
on the floor of one room (labeled “emission room”); the mean sound pressure level is mea-
sured in the receiving room. The relevant measurement standard usually is ISO 140-7 [43]
or ASTM 1007 [44].

The impact noise level is directly measured in the receiving room. However, this sound
level value is sensitive to the amount of acoustic absorption inside the receiving room: This
would eventually mean that according to the fittings in the room, one would pass or fail the
impact noise criteria. In order to avoid this inconvenience, the usual rule is to standardize
the result by the reverberation time.

The standardized impact noise level \( L_{nT} \) is given by

\[
L_{nT} = L_1 + 10 \log \left( \frac{T}{T_0} \right)
\]

where \( L_1 \) is the mean sound pressure level in the reception room, expressed in dB, \( T \) is the
reverberation time in the receiving room, expressed in s, and \( T_0 \) is the reference reverbera-
tion time (usually 0.5 s).

The presence of a ceiling underneath the floor will of course affect the results. Some
standards do take this into account (e.g., ASTM E1007 [44]).
The good news is the tapping machine is reproductive enough. More to the point, it does manage to provide useful data for impact noise prediction, for example, using standard ISO 15712-2 [45]. Now for the bad news: While it is a useful tool for the acoustician, it has trouble correlating with the eventual annoyance from impact sound. This is due to the fact that the generated impact spectrum is poor in the low-frequency range (which is not that surprising, as it was initially developed to try to imitate the impacts from high-heeled shoes). Unfortunately, one may have experienced that a bare-footed person walking on tile does not generate any greater impact noise than walking on a carpet, as this mainly is a low-frequency problem; yet the tapping machine will make a sizable difference out of it. In order to introduce this kind of impact, some countries have been using a rubber ball or even a small tire [46] as an impact sound source. Such a procedure has been investigated [47, 48] and is now considered in an EN/ISO project [49].

3.4.4 Rain Impact Noise

Rain impact noise can be quite significant on light roof elements. In order to help users compare the acoustic performances of roof assemblies or even constructive elements (e.g., roof trapdoors), a test procedure in the laboratory has been developed in standard ISO 140-18 [50]. Of course, the softer the roof covering, the quieter the rain impact noise will be. For modern designs it may be possible to use vegetated roofs [51] that provide a higher sound reduction index value and better impact performances than the standard roofs, while featuring extra acoustic absorption and sustainable development qualities.

3.4.5 Walking Noise of a Floor Assembly

Impact noise transmission concerns the case of the impact machine located on the floor of one room with the sound level measurement held in the receiving room. The walking noise of a floor assembly is assessed by performing the measurement in the same room. Of course, one has to make sure that the noise generated by the impact machine is smaller by at least 10 dB than the walking noise radiated by the floor (this may actually entail some adaptations to the impact machine).

3.4.6 Single Number Rating

In order to help speed up the rating of floor assemblies, one usually relies on a so-called single number rating. This is an obvious simplification, as instead of working on the usual six octave bands (125 to 4000 Hz) of building acoustics, one now uses one single value. Now for the bad news: There are a few rating systems around. To try to simplify things, ASTM uses the Impact Insulation Class (IIC), which features a sliding contour [52]. The curve of interest (sound reduction or sound insulation) runs flat until 250 Hz, and then descends 3 dB per octave to 1000 Hz, and 13 dB per octave from 1000 Hz to 4000 Hz. One glides the contour over the sound reduction or sound insulation curve tested until the sum of positive deviations is no greater than 32 dB and the maximum positive deviation is 8 dB. ISO uses the $L_{nw}$ system [53], which is nearly identical save that the starting point is at 100 Hz and the endpoint at 3150 Hz.

3.4.7 Impact Sound Reduction

Everybody knows about the positive effect of a carpet on the impact sound reduction of a floor assembly. But is that really true? Let’s create a simple experiment with a concrete floor
on which a person is walking with standard shoes, and part of the floor is covered with a carpet. Should one go underneath and listen, it will be pretty obvious whether the walker is evolving on bare concrete or on carpet. Now let's have the walker remove his shoes and evolve again; this time it will be quite difficult for the listener underneath to decide whether the walker is located on the bare concrete or on the carpet.

The impact sound reduction coefficient of a floor covering is defined as the difference between the impact sounds measured in the receiving room of the laboratory with the impact machine located in the emission room on a reference floor (typically a 14 cm thick reinforced concrete slab) without and with, respectively, the floor covering under investigation. The measurement is typically carried out using standard ISO 140-8 [55] or ASTM E2179 [56].

### 3.4.8 Walking Noise of a Floor Covering

Nowadays one often is interested in the walking noise of the floor covering. This is assessed by performing inside the emission test room of the laboratory an impact sound measurement on a reference floor (typically a 14 cm thick reinforced concrete slab) with the floor covering under investigation. This can presently be carried out using EN standard 16205 [57]. The relevant quantity is written $L_{new}$.

### 3.4.9 Computation

A word of caution: Most of the time a crude model will not do, as the problem is more complicated than with sound reduction. For rough comparison purposes, one can use the rather crude expression

$$L_n = 133 - 30 \log(e) - 10 \log(V) - 3$$

where $e$ is the thickness of the floor, expressed in cm, and $V$ is the volume of the receiving room, expressed in m$^3$.

As of now, prediction models for the assessment of the impact noise of a floor have not yet been developed, especially when dealing with floors other than concrete. On the other hand, prediction models for the assessment of impact noise transmitted from one room to another are quite developed (they often are one option within a program that also deals with the sound insulation [15]).

### 3.4.10 Impact Noise on a Wall

So far in this book impacts have been considered as occurring on a floor. What about their occurring on a wall? This is not such a far-fetched problem, as one may face a ball being playfully bounced against a wall by a child, but also a noisy switch being fixed to a wall. More to the point, the acoustician usually looks at the impact sound performance of the floor prior to deciding on the noise reduction measures to be applied to the piece of equipment to be implemented on it, so a similar acoustic assessment of a wall on which a piece of equipment (e.g., a switch or a tap) will be installed is of interest. This is of particular importance when dealing with the noise generated by the operation of such a piece of equipment.

A small impact machine (known as pendulous hammer) has been developed for that matter and tested on various types of structures, including wooden structures [58].
3.4.11 Standards and Regulations

There are quite a number of standards and regulations pertaining to impact noise transmission (e.g., [21, 25–29]). A few of them are given in the various chapters of this book regarding the main types of construction. Typically, there often are maximum impact sound level values required for specific types of construction (e.g., dwellings, schools, etc.).

In addition, some sustainable development standards (e.g., HQE in France) require the floor covering to have been subjected to an impact sound measurement inside the test room. The Swiss Engineers and Architects standard SIA 181 has taken provisions regarding the matter of noise induced by the manipulation of service equipment. A small impact machine (known as a pendulous hammer) has been standardized to assess the impact noise performance of the walls on which such equipment is mounted [59].

3.5 ACOUSTIC ABSORPTION AND REVERBERATION TIME

This chapter briefly outlines the basics of absorption and reverberation time. More explanations are given in Chapter 6.

3.5.1 Experiencing Reverberation

On entering a space, one has probably experienced a feeling like “it sounds dead” or “it sounds lively.” This has often been a problem for performers when deciding on how much volume they should turn out, as different places of similar capacity may turn out to sound differently. More to the point, one has probably experienced trouble with the understanding of speech messages in a lively space. All these feelings are linked to the reverberation of the space (the longer the reverberation, the livelier the room will be perceived).

A professor, W. Sabine, found out that according to the number of cushions brought by his student inside the rather uncomfortable lecture theatre, the space sounded more or less lively. This eventually led to the notion of absorption quantity.

3.5.2 Acoustic Absorption

An absorptive material is a porous or fibrous material in which the vibrations of air are turned into heat when scraping against the walls of the cavities. The efficiency of such a material is characterized by its absorption coefficient, theoretically ranging from 0 (reflective) to 1 (absorptive). In practice, the absorption coefficient value often appears as greater than 1 in commercial leaflets due to reverberant room measurement techniques (cf. Section 2.11.4.3). Measurements are carried out in a reverberant room (i.e., in a diffuse field where sound is supposed to be incident from all directions), typically on a 10 m² (according to standard ISO 354 [60]) or 6 m² (according to standard ASTM C423 [61]) room. It also is possible to assess the absorption coefficient under normal incidence using a wave tube according to ISO [62] or ASTM [63, 64] standards, but the relevant absorption coefficient value under normal incidence does differ from the one in the diffuse field, and picking up the pieces is not a task for beginners [65].

One may care to note that an absorptive material may be hidden by a cladding, but only as long as it is not airproofed. This is a significant difference compared to thermal insulation, where one can keep the thermal insulation performance using plasterboard in front of the insulation.
Often there is confusion caused by architects and contractors indifferently calling insulation a thermal insulation material or an absorptive material. While some materials actually manage to do both (e.g., a mineral wool), most of the time they are associated with a water barrier made of an airproof foil: This means they are no longer absorptive in the middle- and high-frequency range.

### 3.5.3 Reverberation Time

Reverberation time (RT) is a bit similar to the time constant of a physical system: The longer the time value, the greater the stability, but on the other hand, the slower the reaction to a change of excitation. One can experience it when practicing music: In a large church one can hear the organ sounding for several seconds after the key has been turned off (but one will also experience trouble understanding the articulation of consonants in such a space); in a small upholstered meeting room there will not be any hope of sustaining sound (but one will also easily understand the articulation of consonants in such a space). This hints at two important factors: Volume (the greater the volume, the longer the RT) and acoustic absorption (the smaller the absorption, the longer the RT).

The reverberation time is defined as the time span needed for the sound level to decrease by 60 dB after the sound source has been cut off. Another quantity, named early decay time (EDT), deals with the first 10 dB of decrease.

More RT-based indicators are discussed in Chapter 6, which is devoted to room acoustics.

### 3.5.4 Spatial Sound Level Decay

Reverberation time is not always suited as a descriptor of the internal acoustics of an enclosed space; for example, an encumbered flat space with a reflective low ceiling may feature a reverberation time well under the 1 s mark (due to diffusion effects on the fittings), while its users will find it uncomfortable due to sound propagation by means of reflections on the ceiling. This is a kind of situation encountered in open space offices or industrial spaces. To cope with the task of describing the acoustics of such spaces, one uses the notion of spatial sound level decay. When measuring away from an omnidirectional sound source the sound level value first decreases rather sharply with the distance, as the direct sound field of the sound source is predominant. Next, the reverberant sound field is an important contributor (intermediate region), and then later (far field), it is much greater than the direct field, as illustrated in Figure 3.3.

The spatial sound level decay ($DL_2$) is defined as the rate of decay per doubling of distance. It is measured in the intermediate region according to standard ISO 14257 [66] using an omnidirectional sound source. Prior to the introduction of this quantity, a French law text had used it for industrial spaces, either fitted or not [67]. Lately, ISO 3382-3 has proposed a measurement procedure for open-space offices [68]. The result may be expressed as a single number quantity for either a pink noise or a speech noise.

**Note:** For quicker assessment (or when the dimensions of the room are not compatible with a spatial sound level decay measurement!), one sometimes uses the so-called amplification, which is the difference between the sound pressure level measured at 10 m from an omnidirectional sound source in the space under study and the sound pressure level measured at 10 m from the same sound source under free field conditions.
3.5.5 Reflecting, Focusing, and Scattering

So far we have not bothered with the shape of the room. Unfortunately, it will play a role. To start with, a concave surface will usually tend to focus sound energy as illustrated in Figure 3.4. While this can be exploited for some effects, it often proves to be a hindrance. That can be prevented using either an absorptive material (that will absorb sound energy) or a scattering material (that will redistribute the sound energy over a large area instead of a specific direction) (cf. Section 6.6).

Note: Should the relevant acoustic treatment be mounted on the wall as a separate fitting, please do keep in mind that its mounting may affect the overall sound reduction index (e.g., due to the small air gap between fitting and structural wall, or simply due to the fixation holes!).

3.5.6 Standards and Regulations

There are a few standards and regulations pertaining to reverberation time and equivalent absorptive area [69]. A few of them are given in the various chapters of this book regarding the main types of constructions. Typically, one may care to note the following constraints:

- There are limits, expressed as noise levels, regarding the noise exposure of workers, or the danger limit for people exposed to high-level music. Introducing absorption in the
room may help reduce noise propagation and sound level value, and it is often recommended in the relevant guidelines.

- There often are maximum reverberation time values required for specific types of construction (e.g., dwellings, schools, etc.), as well as minimum equivalent absorptive areas for such types.

### 3.6 VIBRATION CONTROL

#### 3.6.1 Foreword

Building vibrations is a domain of its own. In this chapter we will limit our interest in such vibrations that can actually radiate audible or perceptible noise.

#### 3.6.2 Sources of Vibrations

Vibrations in a building can be generated by various vibratory sources. Here are a few of them:

- Mechanical equipment
- Users’ equipment
- Rail transportation corridor nearby
- People walking or dancing
- Wind on the façade or roof

#### 3.6.3 A Few Standards and Regulations

While standards and regulations pertaining to noise exposure have steadily been developed over the years, texts pertaining to vibration exposure are not as obvious. This is in part due to the lack of data on the subject. While aspects covering excessive vibration levels are usually covered due to the risks to the structure of the building, aspects covering annoyance are not as completely covered. The international standard ISO 2631 [70] considers three vibration spectral limits, for comfort, work efficiency, and danger, respectively, with the highest sensitivity in the 4 to 8 Hz interval.

When it comes to noise generated by vibrations, there are regulations in a few countries [71]. Those typically set a maximum $L_{A_{eq}}$ value over a given time span. For example, a Swiss federal regulation [72] requires the $L_{A_{eq},1h}$ generated by rail transport not to exceed 30 dB(A) in nighttime.

#### 3.6.4 Vibration Control

Vibration control philosophy is a bit similar to noise control, as one can act at three different stages:

- Reduction at the source (i.e., minimizing the amount of vibratory energy generated by a vibratory source through either better design or resilient decoupling from the structure)
- Reduction along the path (i.e., implementing expansion joints along the propagation path)
- Reduction at the receiver end (i.e., box-in-box construction)
3.6.4.1 Reduction at the Source

Reduction at the source of course happens to be the most efficient way to deal with a problem of vibration-induced noise, as it will prevent spreading vibratory energy throughout the building. Now for the bad news: it will also not be possible under any circumstances, as it will certainly entail an interruption of the operation of the equipment involved in order to implement the required measures. This is especially true of rehabilitation projects. For example, when dealing with a freezer serving a whole building, the users may not be happy at the length of time required to disconnect the equipment, build the resilient supporting elements, reconnect everything, and test it prior to recommissioning. Even worse, when dealing with a railway line, there usually is no hope of implementing vibration control measures without a significant interruption. When small gains (up to 5 dB at 63 Hz) are looked for, there is a technique for light rail systems using a resilient fastening of the track on the sleepers. As the sleepers do not need to be removed from the track bed, this does not entail speed reductions, and it can be implemented at a suitable time, for example, during the night break of operations [73].

3.6.4.2 Reduction along the Path

Reduction along the path is tricky, to say the least. In aerial acoustics over distances under the 100 m mark one faces the same propagation medium. When dealing with vibrations in the ground, the propagation medium can be rock somewhere and sand somewhere else, not to mention all those forgotten structures left interred. This may sometimes give surprising results when it comes to the propagation in the ground. One cannot make the economy of a diagnosis. This is made through vibration measurements at given distances from the source, and whenever possible, the soil test excavations are used too.

If the vibrations are mainly propagated on the surface, it may be expedient to try to use a vibration barrier [74]. This is efficient as long as no objects or harder ground are located nearby and likely to reflect energy short-circuiting the barrier.

It is also often possible to implement vibration control measures between the foundations and the superstructure of the building. This is performed using springs or resilient elements that are typically located on the top of the foundation pillars or on top of the basement structure. Close cooperation is needed between the structural engineer (as the performance of the springs or resilient elements will depend on the accuracy of the load applied on those elements), the acoustic engineer, and the safety engineer (as consequences of a fire or an earthquake must be investigated).

3.6.4.3 Reduction at the Receiver End

As a last-ditch effort, vibration reduction measures can be applied at the receiver end.

Those will typically entail a box-in-box construction, with the rooms to be protected built using a concrete slab supported by resilient pads or springs over a stiff concrete structure. Of course, such a scheme does complicate the actual construction work.

3.6.5 Noise Generated by Vibrations

Vibrating surfaces will radiate a sound power level. Usually this is in the low-frequency range. For example, inhabitants of downtown Parisian dwellings are quite accustomed to the deep grumble (63 Hz) from the underground rail lines. Noise radiation will actually appear well before any vibratory sensation.
The sound power level $L_w$ radiated by a wall of surface $S$ excited by vibrations can be expressed as

$$L_w = 10 \log(S) + L_v + 10 \log(\sigma) + K$$

where $\sigma$ is the radiation factor of the wall, $L_v$ is the velocity level reference $10^{-6}$ m/s, and $K$ is a constant.

The radiation factor $\sigma$ is equal to:

- $1$ if $f > f_g$
- $0.45 \sqrt{P/\lambda g}$ if $f = f_g$
- $1/\pi^2 (P \lambda g/S) \sqrt{f/f_g}$ if $f < f_g$

where $P$ is the perimeter of the surface.

The coincidence frequency $f_g$ is given by

$$f_g = c^2/(2\pi d) \sqrt{12 \rho (1 - \mu^2)/E}$$

where $E$ is the Young’s modulus (in N/m$^2$), $d$ is the thickness of the plate (in m), $\rho$ is the volumetric mass of the material, and $\mu$ is the transversal compressibility coefficient.

Here are a few examples of $10 \log(\sigma)$ values [75]:

- For a 24 cm brick wall: 0 dB.
- For a 7 cm concrete: Range –15 to –5 dB until 500 Hz, then 0 dB above.
- For a 13 mm plasterboard: Range –15 to –5 dB until 2000 Hz, then 0 to 5 dB above.

### 3.7 CONSTRUCTION NOISE

There usually are a few rules pertaining to the construction. In order to reduce annoyance to the neighborhood, there will typically be a specific time span to be complied with (e.g., 7:00 a.m. to 7:00 p.m. at most), with night work and weekend work allowed on a case-by-case basis.

Most of the time, the core of the requirement is contained in the building permit, that states the allowable hours of operation and the eventual restrictions (e.g., more stringent hours and sometimes the allowed methodology of demolition and construction) [77–79].

When the building site is located in a sensitive environment, it is not uncommon to have a noise monitoring system installed and regular measurements performed.

In some situations the building permit can be a real killer. As an example, in Paris on the famed Champs Elysées, the regulations in force require the waste bin to be brought on the curb at 6:00 a.m., and it must be removed no later than 7:00 a.m.! Needless to say, the squeaking and banging noises from these operations are not pleasant to the neighborhood.

**Word of Advice:** While there are a few legal requirements in force, it is not a bad idea to try to contact the neighborhood to explain what the building operation will be and when a few noisy phases will occur [77, 80].
3.8 A FEW STAGES OF BUILDING CONSTRUCTION

A building project is typically carried out over several phases (please note that in smaller projects some of those phases may be grouped together!). Here is a brief description of those phases.

Sketch, feasibility sketch: Analysis of the program drafted by the end user, draft sketches, technical and architectural notice, preliminary economic estimate. Note: This is the right moment to point out the potential requirements and problems of a project, for example, try to get a sensible layout of the rooms inside the building with regards to one another and with regards to the potential exterior environment.

Preliminary design: Analysis of the program (complements if need be), checking that the sketches are compatible with the technical and architectural requirements, technical notices, architectural notice, cost estimation, general drawings. Note: This is the right moment to ask for specific constructive elements (e.g., a plain concrete slab, an acoustic door, etc.).

Design development: Verification of compliance with the regulations in force, adaptations and final complements of the program, finishing touches to the administrative and technical documents, drawings of floors and cross sections, architectural details, prescriptions regarding architectural and technical items, final cost estimate. Note: This is the time to be committed to the budget (do make sure nothing was forgotten!).

Final development: Analysis of the choices made during design development, detailed notices and drawings. Note: This is the right time to call for suitable sealing around the various networks or constructive element; this is also a suitable time to require acoustic testing of some assemblies.

Tender document: Elements to be addressed by the contractor in the submission, using the final development document set. Note: This is the right time to require from the contractor a specific methodology or a list of conditions to be able to properly check the work.

Assistance to contractor selection. Note: This is the right time to make sure one will not be plagued with a contractor who was the lowest bidder but who is unable to properly perform the required work!

Visa: Visa of execution drawings and equipment selection, choosing architectural and technical solutions on the basis of the synthesis of the project. Note: This is the right time to prevent a problem through the erroneous selection of unsuitable material or equipment by the contractor.

Site supervision: Participation in the organization of the work, checking that work is proceeding according to the requirements. Note: In France one says “pas vu pas pris” (not seen not catched). One definitely must be able to check such important details as, for example, the absence of elements likely to short-circuit resilient fasteners or pads, the use of a concrete or plaster finish instead of a glued plasterboard, etc.

Commissioning: Assistance to the complete commissioning through measurements. Note: This is the right time to emit any statement regarding the noncompliance of the contractor’s work with the acoustician’s specifications. This is also the right time to explain to the end user or his representative how to use the facility that is being delivered.

By the way, a project usually requires some demolition work at the beginning of site work. Whenever this is carried out with some thoughts for sustainability, the politically correct designation of this phase is deconstruction.
3.9 REFURBISHMENT

Rehabilitation is a quite usual procedure in Europe [81]. There may be quite a few reasons to go for it. To start with, older buildings usually feature a higher legal potential occupation ratio per ground square meter than the ones allowed by normal recent constructions. More to the point, it helps the urban planners to keep a homogeneous urban appearance. Last but not least, it helps save time if the walls and floors (and sometimes even the roof) are kept; administratively speaking, it may also speed up things, for when the envelope of the building is kept, one often will solely require a fitting-out permit instead of a full building permit. On the negative side, it is not uncommon to lack some suitable space to route the ducts and pipes through. Quite often, the walls and floors do not feature high enough an acoustic performance and must be completed using plasterboard and mineral wool stud-mounted elements that will reduce the available floor dimensions and height.

In such a kind of project it is necessary first to perform a diagnosis of the existing building in order to find out how it is built and where the sensible points are. Each specialty will have to perform its own diagnosis. One should remember that a structural diagnosis usually can be a bit destructive, as the structural engineer will typically cut through floors and walls in order to assess their composition, so the acoustician must make his measurements before.

Note: There is a strong need for coordination between the interested parties, as depending on the planned sketch of the future rooms inside the building, some zones will be more sensible than others. More to the point, everybody must be aware of each other’s needs.

The diagnosis through measurements will feature:

- Sound insulation measurements between rooms when the walls are kept. Note: This measurement will help assess the potential flanking transmission by those walls, as well as the potential sound insulation of those rooms.
- Sound insulation measurements and impact sound measurements between rooms at different floors. Note: This measurement will help assess the potential sound insulation between floors.
- If applicable, vibration measurements on the floors. Note: This will help assess the eventual noise generated by vibrations (e.g., from rail lines nearby) and vibration levels inside the building.
- An acoustic diagnosis of the site will be performed as per a regular new construction project (i.e., assessing the sound level values on the site and finding out what the potential noise sources around are, as well as the potentially sensible zones around). Note: Do keep in mind that usually a rehabilitation project will entail some unbuilding prior to the actual construction work. Under the nice words one can already hear the concrete breakers hammering away, so one had better have a good look at the location of the nearest neighbors, especially those who are structurally linked to the building. It will probably be necessary to explain to the neighbors the basics of the project and point out that while some phases of the work will be noisy, they will be kept to a minimum of duration and their time schedule will be adapted, while appropriate noise reduction measures will be implemented.

It must be stressed that the diagnosis will constitute the testimony to the acoustic performance of the building prior to any work. It is not only a basis for the acoustic studies (from which predictive computations will be elaborated), but it is also often a compulsory step to be able to prove ultimately that the initial acoustic performances of the building have not been deteriorated [81].
In the particular case of historical buildings things can get quite complicated, as usually the façades and even the roofs must be preserved. In some cases, it is even necessary to preserve some interior spaces (e.g., because of paintings on the walls or ceilings). Under such circumstances the acoustic objectives must be adjusted on a case-by-case basis, and specific solutions must be elaborated (e.g., introducing intermediate spaces around in order to prevent direct transmission to other spaces of interest, or working on the other side of the partition or floor using such doublings as a floating floor, a plasterboard ceiling, or half wall, with mineral wool in the void).

A special mention must be made regarding performance halls: Those usually are considered historical landmarks, and the end user may wish to preserve (or sometimes improve) much more than the sound insulation characteristics (cf. Chapter 6).

### 3.10 NOTIONS OF SOUND MASKING

#### 3.10.1 Foreword

Sound masking has enjoyed a few developments due to the increased use of electronics, but it is by no means a recent method. In antiquated times, the Romans would often use the sound generated by a small fountain in the atrium to try to mask noise from one room to another.

Nowadays, everybody has had a few occasions to wonder about the sound insulation of one’s room. Actually, the perceived intrusion of noise is only one of a few contributors to the global noise level in the room (cf. Figure 3.5). When those contributions are well balanced, usually one does not especially overreact to the various sound stimuli, but if one of those contributions is much greater than the others, then you can bet that some noise annoyance will soon be felt by the inhabitants. A very classic example of sound masking is that of the rehabilitation of dwellings: In a first phase, an acoustician will be required to devise a significant improvement of the façade insulation; within a year, he or she will come back and ask for an improvement of the sound insulation between flats. What is happening? Prior to the rehabilitation the noise transmitted from outdoors through the façade and the noise from other flats were more or less balanced; when the façade sound insulation was improved, then

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**Figure 3.5** Noise contributions in a room.
the background noise level in the flats was significantly reduced and any noise from other flats was plain to hear and identify.

### 3.10.2 Sound Masking

As implied by the name, sound masking does not eradicate a particular noise signal (known hereafter as a distracting signal); it merely tends to hide it from the potential listener. So, one has to use a sound system that will raise the background noise level value above the sound level value of the distracting signal (e.g., a voice). Of course, such an increase cannot be performed with too high a sound level (e.g., over the 45 dB(A) mark the sound masking signal will start being perceived as another distracting signal too). More to the point, the spectral contents must cover those of the distracting signal. Last, in order to avoid being distracting, the masking sound usually is steady.

Adjustments to both noise level and spectral content should be left to the specialist (actually, one of the first technical ventures in this field featured loudspeakers on top of open-plan office furniture panels that unfortunately had controls readily accessible to the user, and that spelt its demise). Nowadays, systems are implemented using a computer simulation, and their loudspeakers are often also used for such purposes as background music or PA messages.

Please do remember that the masking sound must not be recognizable by the user, as it would then become a further distraction in the soundscape, and it could even become one more nuisance. For this reason one must refrain from using music as a masking sound (while it might be enjoyed by some people, it will annoy others).

Examples of use are open-plan offices, waiting rooms, security-minded offices, etc.

### 3.11 A Word About Privacy and Security

#### 3.11.1 Foreword

Everyone has been subjected to the acoustics of offices or dwellings with varying degrees of sound insulation performance. One has probably noticed that when the background noise level value is especially low, it becomes easier to hear what is going on next door. One may also have found that in flats during the daytime, one merely feels a presence in the next flat, while at nighttime it may be possible to recognize voices.

Actually, the ability to hear and understand what is being said in a room depends on the intelligibility of the message (more about that will be covered in Section 6.5). This means that on the receiving side it will mainly depend on the sound insulation between the rooms of interest and on the background noise level at the receiving end.

As a rule of thumb, the minimal value of the sound insulation $D_{nTw}$ needed to ensure privacy is 45 dB.

#### 3.11.2 Privacy and Security

Privacy means that under normal circumstances (i.e., a normal spoken voice on the emitting side, and a background noise on the receiving side featuring the usual mechanical services and small chatter), one will not understand what is being said at a normal voice level on the emitting side. This will entail a minimum 45 dB sound insulation. But should the voice level be raised or the background noise level drop, this will be an entirely different matter.
If one wants to avoid such a situation, such contingencies have to be taken into account, and a sound insulation of 55 dB is a minimum.

But there is worse to come: Should somebody be intent on eavesdropping, there are quite a few tricks much more sophisticated than the old ear on the partition, that is, a vibration captor on the wall or floor (cf. Section 3.12.17), or even measuring the vibration of such a surface using laser equipment.

Water-filled ducts usually are poor acoustic conductive paths. But empty or air-filed ducts are another matter, and it may be necessary for security purposes to fit them with a vibrator too.

Masking sound comes handy in such circumstances. For simple cases, one will merely have a sound system adjusted so as to ensure that the background noise levels around the protected room are more than 10 dB above the transmitted speech sound. For more complicated cases, one will also introduce vibration generators on the walls and floors in order to disrupt any attempt at measuring the vibrations of the envelope of the room.

3.12 EXAMPLES

3.12.1 Is Such a Heavy Concrete Wall Insulating?

When they had to prescribe the means of sound insulation between two rooms, both the small contractor and the end user of a small extension project decided a heavy-cast concrete wall would do fine. However, when the time for trials came, both were startled to discover that some rather high-pitched transmitted noise could easily be heard.

Looking closely at the work, an acoustician invited to have a look quietly pointed out that the cause was to be found in the improperly filled holes in the wall that previously connected both sides of the casting frame.

**Lesson Learned:** The overall acoustical performance is dependent not only on the chosen material, but also on the modus operandi.

3.12.2 A Small Dance Floor

A small dance room (capacity: 10 persons maximum) had been fitted in a public building in what formerly used to be a small storage space. The floor covering was of a PVC type.

When people were dancing on that floor, the lighting fixture in the service dwelling underneath made strong oscillations. More to the point, the dancers were complaining of the uncomfortable conditions on such a floor (Let’s face it: The floor was too stiff for the dancers but too weak for acoustic purposes).

The whole floor assembly was eventually replaced by a thick concrete slab and a wooden floating floor on resilient joists, which solved the problem.

3.12.3 Impact Noise Reduction

The new owner of an old flat decided that it would be nice to get rid of the tired old-looking carpet in the living room. He decided to have it replaced by marble tiles. In order to reduce impact sound transmission to other parts of the building, it was decided to lay them on a resilient screed. As soon as the work was finished, the neighbor underneath complained of too high impact sounds. It turned out from the measurements that while the impact noise levels did comply with the legal objectives applicable for new construction, they were slightly greater than those measured with the old carpet. The owner eventually managed
to get an agreement with the condominium to keep his new floor covering, as internal rules had provisions for such a case.

Lesson Learned: It may not be sufficient to look at the legal requirements; degrading the acoustic quality may often be considered a problem.

### 3.12.4 A Fan

The acoustician had been called in a flat where the tenant was experiencing a strange sensation. On arriving there he found that there were strong stationary waves in the 16 Hz third octave band in the bedroom: The noise levels measured close to the walls and in the middle of the room were higher by 10 dB than the other levels. It eventually simply turned out that the tenant at the previous floor had mounted an unbalanced ceiling fan.

### 3.12.5 Misusing a Computer Model

One day the supervisor of a public facility building site phoned the acoustician and expressed his dissatisfaction with the prescriptions: All required wall thicknesses were wrong, e.g., a 12 cm concrete wall was sufficient where the acoustician had required a full 20 cm wall.

It turned out that the supervisor had used a commercial computer model that was suitable for dwellings. When applied to large volumes such as a conference room, the correction for the depth of the receiving room was such that it would theoretically enable the use of much smaller separating walls.

In another example, there was a project of offices being built close to a very busy motorway. While the acoustician prescribed the façade characteristics bearing in mind that there would be partitioned offices along the façade, the contractor considered the whole open-space floor. This resulted in a 10 dB difference on the sound reduction index of the façade.

### 3.12.6 A Window

A manufacturer writes in its technical data that the sound reduction index of its window is 33(1; –4). What does that mean?

Well, this is a single number according to ISO 717-1, stating the $R_w$ value and the corrective terms to access the pink noise and the road traffic noise sound reduction index values.

This gives

$$R_w = 33\, \text{dB}, \quad R_A = R_w + C = 34\, \text{dB}, \quad \text{and} \quad R_{Atr} = R_w + C_{tr} = 29\, \text{dB}$$

Lesson Learned: Be careful should one be dealing with specifications involving a road traffic noise reduction index, as most distributors and contractors are not always aware of such subtleties!

### 3.12.7 A Glued Plasterboard

When using concrete blocks, the architect often wants a proper finish applied to the wall. In order to improve its sound reduction performance, the acoustician usually wants a 2 cm minimum plaster or concrete finish to be applied. However, due to the task being quite time-consuming, it is quite tempting for the contractor to use glued plasterboard.
The problem is one will end up with a 1 cm gap between the structural wall and the plasterboard, and more to the point, the concrete blocks will remain as porous as ever. In the end, one will discover that while the general visual aspect is satisfying, the acoustic target is not met due to a strong resonance.

### 3.12.8 A Glued Calibel (Plaster on Mineral Wool)

Calibel is a complex made of a 50 mm glass wool factory assembled onto a 10 mm plasterboard. This is a kind of product often used by patrons to try to improve the sound insulation of their premises. However, due to its dimensions, while it can be effective for speech transmission prevention, it can actually degrade the sound reduction performance in the low-frequency range (e.g., when attempting to reduce the noise from the television set next door).

In a particular case when the acoustician had been attempting to reduce the noise of a washing machine transmitted through a light wall from the kitchen next door, the contractor decided to use Calibel instead of plasterboard on metal studs. The result was clear enough, as the measurements actually showed that the final situation was worse than before by 3 dB due to the low-frequency range transmissions.

In another example the contractor found it more expedient to use a Calibel instead of a stud-mounted plasterboard doubling that had been required to improve privacy between two rooms separated by a light partition. The result was startling: With the glued complex added on the original partition, the sound insulation had been reduced by 3 dB at 500 Hz.

**Lesson Learned:** Do not trade a stud-mounted doubling for a glued doubling.

### 3.12.9 Long Reverberation Time in an Anechoic Room?

When commissioning its new anechoic room a university laboratory decided to have students perform reverberation measurements inside. To the consternation of the professor, several students reported a quite long reverberation time in the 4000 Hz third octave band. After giving them a proper dressing down (how could one expect a long reverberation time with so much acoustic absorption around?), he ordered them to do a proper measurement. Back they came with similar results. The baffled professor then personally performed the measurement and got the same results too. It eventually turned out that rodents had nested in the mineral wool and screamed at 4000 Hz whenever they heard such a sound.

**Lesson Learned:** You may believe your measurements, but only if you can explain them!

### 3.12.10 Ruined Absorption

A project had required some absorption in the room, and the required amount had been provided using a perforated plasterboard ceiling. Unfortunately, the reduced time frame drove the architect to order the painters to proceed hastily. When this was finished, all the holes and porosities had been clogged, turning the previously absorptive ceiling into a reflective one.

In another case, a laboratory had enjoyed a poor man’s semianechoic facility made of a soundproofed cabin featuring mineral wool protected by perforated metal plates inside. One day an official came visiting the lab and decided a repaint was in order. By the time the lab technician realized what was going on, his semianechoic test room had been turned into a fairly reverberant room!

**Lesson Learned:** Always make sure the reasons for such materials have been explained.
3.12.11 An Improvement Turned Sour

An acoustician got a phone call that left him with a flea in his ear: An architect told him that his absorptive treatment prescription for a small performance hall was an absolute disgrace. Puzzled about this project that did not ring any bell, the acoustician eventually found out that this particular architect had simply copied the text from the prescription book of another of the acoustician’s projects; in doing so, he thought he had made a little improvement by replacing this itchy yellow or pink material by friendlier polystyrene!

Lesson Learned (at great cost!): Do not copy! More to the point, an absorptive material features an airflow resistivity, if you know that you won’t use polystyrene as an absorptive!

3.12.12 A Bridge

Here are a couple of examples of bridge vibration events (and kindly remember, some constructions are built as a bridge!).

In the mid-19th century a troop marched on a river bridge in France. According to some stories, the rhythmic pace of the soldiers was close to the resonance frequency and started to excite the bridge, and this was considered much fun—until the bridge collapsed because of it. A similar story was reported in Great Britain for the Broughton Bridge in 1833.

Another famous story concerns the Tacoma Bridge in the United States that was excited by the wind in 1940. The excitation eventually reached such an intensity that the bridge broke. There was a film capturing the whole sequence [76].

3.12.13 Structure-Borne Rail Noise

Here are a couple of examples of structure-borne rail noise control attempts.

Foreign investors bought a Parisian office building also housing cinemas and shops with the idea of turning it into a luxury hotel. When they realized that noise was generated in the cinema facility due to an express rail line and a subway line (which also had the bad grace to be located at the ideal spot for the parking ramp), they simply went to the transportation authorities to ask for those lines to be deviated (quite simple, isn’t it?). Of course, the bewildered authorities turned the request down. That project eventually featured projection theatres built as a box in box.

Lesson Learned: Do not even dream of deviating a rail line!

In another project, in order to achieve the required structure-borne noise reduction in the office building above a railway tunnel, the tracks from the suburban rail line were subjected to vibration control measures using a resilient mat under the ballast. Such a move was only made possible by the closure of the line during 1 month due to track and infrastructure maintenance.

Lesson Learned: At the source vibration control may be possible with proper planning.

In another rehabilitation project it was wondered whether it would be possible to reduce the structure-borne noise from the subway inside the basement of a historical building. Investigations quickly showed that there was a maze of sewers, ducts, and technical passages between the walls of the subway tunnel and the foundations of the building. More to the point, part of the tracks had already been treated to a resilient mat under ballast. With propagation paths coming from practically everywhere, it was found totally uneconomical to try to create a clear resilient separation between the foundations of the building and the tracks, and the idea of structure-borne reduction was dropped from this project.
3.12.14 Shop Offices and Dwellings

An art deco building located on the famed Champs Elysées in Paris housed a luxury shop, as well as offices and dwellings. The owner decided a major rehabilitation would eventually have benefits through a higher rental value, and a project was decided upon.

The diagnosis was performed by the whole design team. It showed that while the sound insulation was quite good at the lower floors with a 53 dB value between floors (that usually were the master’s apartments in the olden days), it steadily deteriorated, with only 38 dB between the last floors (that were the servant’s quarters). It also showed that the structural capabilities of the building were quite limited.

The project called for plasterboard walls and ceilings in order to save weight, while increasing the sound insulation between spaces of the building. Resilient floor coverings were systematically used. One of the difficulties was to find the necessary space to route the new ducting system and install the air handling units, with some of them ending up in a former servant’s room and the others in the basement.

The deconstruction planning and the building planning had to be carefully studied, as the shop at ground level was operating in the end of the afternoon, and there was a hotel next door too. Discussions with their respective operators enabled to them reach an agreement through which the building contractor could perform normal work on weekdays between 10:00 a.m. and 3:00 p.m. The methodology of work was adapted to the circumstances; e.g., sawing under an absorptive enclosure was preferred to the use of a concrete breaker. The only significantly annoying point was the waste removal, as local regulations prescribe the bin to be brought no sooner than 6:00 a.m. and to be removed no later than 7:00 a.m.!

Lesson Learned: Rehabilitation work is possible in a dense urban environment as long as appropriate measures are taken and discussion is kept opened with the neighbors.

3.12.15 Where Is One Supposed to Measure?

An expert to the court was required to perform some noise level measurements in a bedroom of a multidwelling building where the tenant complained about various noises coming from other parts of the building. When he came to perform the measurements he was presented with an empty room where he performed the usual sound level measurements at a height of 1.5 m from the floor. No significant noise event could be identified.

Then it suddenly hit him: If this was supposed to be a bedroom, where was the bed? The tenant looked blankly at him and opened a small cupboard from where he picked up his braid (well yes, he was of Asiatic descent)! When measuring close to the ground, a number of events were at once identified.

Lesson Learned: When somebody complains, it is interesting to perform a measurement at their usual location and not limit oneself to the typical locations indicated in the standard.

3.12.16 Is There an Insulation Problem?

On performing the sound insulation measurements between two cinema projection theatres, the acoustician felt quite confident as he had already designed and built similar facilities along the same design lines. In this particular case, the separating wall between those halls was made of a double concrete wall with an expansion joint in between that should ensure the required performance. So sure was he that he sent a young engineer to perform the measurement while he talked with the end user. To complicate matters, the brand new amplifiers were smelling a bit too hot for comfort, and it was decided that one should not push the
volume too far for the sake of safety of the sound equipment (well, it wouldn’t have done to
burn the amplifiers before the official inauguration by the authorities, would it?). While this
was supposed to be a bit close to the limit in the high-frequency range, it was supposed to be
usable. The young engineer came back and stated that he felt the measurements were OK.

To everybody’s surprise the sound insulation result turned out to be rather bad, so bad that
spectators complained soon after the opening of the facility. On coming back, the acoustician
had the sound system turned on in earnest. While a low-frequency rumble could be heard
on the upper part of the wall, a rather high-pitched noise could be heard close to the screen.

When the acoustician pointed out that such a noise could only come from a hole in the
walls, the architect was adamant that it was not possible, as nobody in his right mind would
have drilled a hole through two concrete walls, and it would be luck that they would match
each other. But the acoustician held his ground: This did sound like a hole. Well, exploring
the wall with his hand, the end user suddenly found a very soft spot and the noise was sud-
denly considerably reduced. Such a double hole had really been drilled (for which purpose
nobody knew!). While he was wondering why his young colleague had not identified the
problem, the end user came up with an explanation that was duly tested and proved conclu-
sive: With a lower sound level on the emission side, it was really much harder to distinguish
the noise radiated by the hole.

That did solve the high-frequency part of the problem (and a good thing that was, as the
speech signal in a projection theatre could then be heard in the other theatre because of it).
Regarding the low-frequency rumble, it eventually turned out that the contractor had left in
place the material used to cast the double concrete wall, and this created a surface coupling
that significantly decreased the low-frequency sound insulation performance.

Lessons Learned:

- Use a high sound level pink noise on the emission side to be able to spot
  weak spots.
- Do not rely on a young unsupervised collaborator to make the assessment, and
  do not take for granted that something will not be done because it is not logical (it might not
  be at the time of analysis, but it briefly made sense to the contractor for reasons of his own).

### 3.12.17 Listening to Conversations through a Floor

A large rehabilitation project involved the demolition of a few concrete structural elements.
In order to ascertain whether some parts of the building could still be kept in operation during
the deconstruction phase, it was decided to perform a diagnosis on one unoccupied floor.
It involved banging on the floor and walls of a room at one end of the building and checking
how much sound energy was lost at each expansion joint using vibration measurements.

When the acoustician analyzed the tapes, he found that after the second expansion joint,
the banging was no longer much discernible. On the other hand, the conversations held in
the room underneath were totally understandable!

Lesson Learned: A properly executed expansion joint is an efficient attenuator; also, eaves-
dropping using accelerometer measurements is possible.

### 3.13 HAVING A GO AT DIMENSIONING THE PROJECT

#### 3.13.1 General

The first step will be an inventory of the applicable regulations and standards: They prob-
ably feature noise limits that have to be complied with, as well as some other acoustic
targets (e.g., reverberation time and sound insulation requirements). In addition, there often is a program that has been drafted for this specific project, and its targets must be checked against legal requirements as well as against technically and economically realistic customs. The next step will be an inventory of all potential noise sources (i.e., determining what the noise levels are likely to be in the various spaces of the project, including its environment). Such data may be found in the program established by the end user’s representative; should that be not the case, a hypothesis will have to be stated and identified as such. There will also be an inventory of all sensible spaces (e.g., bedrooms, etc.) to be found in the program established by the end user’s representative; should it be not the case, a hypothesis will have to be stated and identified as such.

Prior to actually dimensioning the various constructive elements, please kindly remember that:

- The sound reduction index of a wall or floor, and the impact noise level of a floor, measured under laboratory conditions, usually are officially given with ±2 dB accuracy; in practice, it is closer to ±5 dB, and one must take such a value into account to be on the safe side when performing the computations.
- Absorption coefficients are often given with 20% accuracy.
- Sound power levels of a piece of equipment usually are officially given with ±2 dB accuracy; unfortunately, they are often given under operating conditions that may seriously differ from the actual conditions to be encountered in the project.

### 3.13.2 Sound Insulation

Next, one will have to state the sound insulation objectives required for the compliance with the noise limits stated for each space. One may care to remember that the global sound level inside a space is the sum of several contributions (cf. Figure 3.2).

Last, one will have to check that the above-computed sound insulation values are not smaller than the eventual values that are required by the regulations in force. A similar check will have to be performed with regards to the values required in the program.

Those requirements will result in minimal specifications for the envelope of the spaces (floors, walls, etc.).

### 3.13.3 Impact Sound Insulation

One will have to state the impact sound insulation objectives required for each space.

Next, one will have to check that the above-defined specifications in Section 3.13.2 still enable the project to reach the impact sound insulation targets. In the negative, extra prescriptions will then apply (e.g., definition of a resilient floor covering or even a floating slab).

### 3.13.4 Reverberation Control

One will have to state the reverberation time for each space.

The reverberation time may be estimated using Sabine’s formula. One will have to check that the computed values are not greater that the eventual values that are required by the regulations in force. A similar check will have to be performed with regards to the values required in the program.
3.13.5 Mechanical Noise Control

The initial sound level objectives were stated in Section 3.13.2. Now one will have to state the sound level contribution of the mechanical equipment required for the compliance with the noise limits stated for each space. A preliminary computation will have to be carried out, from the circulator (e.g., an air handling unit (AHU)) to the delivery point of interest (e.g., a louver in a room).

In addition, one will have to make sure that the structure is capable of accepting the weight of the equipment under scrutiny, plus its attending inertia mass if required. More to the point, one will have to make sure that there still is enough headroom left according to both work condition regulations and manufacturer’s specifications.

3.13.6 Fire and Safety

One will have to check (or have a specialist check) that the various assemblies of constructive elements comply with the fire and safety regulations in force. Should that be not the case, it is mandatory that the prescriptions be revised accordingly.

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