# Chapter 15
Sound Environments

The study of sound in the environment begins by thinking about the different ways that sound can travel from a source to a receiver. There are five important processes as shown in Fig. 15.1:

- *Direct* sound travels in a straight line path through the air from source to receiver. This is always the path of shortest length.
- *Reflected* sound hits a wall or other surface and bounces off. Reflected sound stays in the room with the source. Some of the reflected sound arrives at the receiver in the same room.
- *Transmitted* sound goes directly through a wall to a receiver in another room. Possibly that occurs because there are holes in the wall. Possibly it occurs because the wave from the source vibrates the wall and the wall reradiates the sound on the other side.
- *Propagated and transmitted* sound is like transmitted sound, but it may follow a long path. It may be propagated through air ducts or as vibrations along the surfaces of pipes or partitions. A concrete floor can propagate the noise of a machine long distances within a building.
- *Absorbed* sound is wasted sound. Absorption is different from the other processes because after absorption there is no more sound. Absorbed sound does not get to a receiver, instead it is turned into heat by friction. Actually, the ultimate fate of all sound is to be absorbed somehow, somewhere. That fact is part of a general truth: all energy that is used in our world (mechanical, electrical, chemical, or acoustical) ultimately ends up as heat.

15.1 Reflections from a Surface

The reflection of sound plays an important role in almost all environments. As noted in Chap. 6, reflection from a surface can be specular or diffuse:

Fig. 15.1 In this cartoon, a source of sound (S) radiates sound that propagates directly to a receiver (or listener, L) by a direct path (D), is reflected from a wall (R), is transmitted through the wall (T), is propagated along the thin panel and transmitted from the end of that panel (PT), or is absorbed on the wall (A)
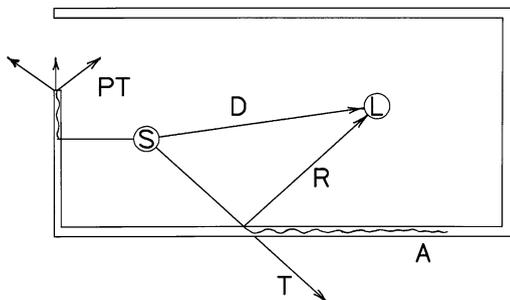
(a) Specular reflection is like a billiard ball bouncing off a cushion on a billiard table. The angle of incidence is the same as the angle of reflection.
(b) Diffuse reflection is like a high-speed tomato hitting a wall. The sound wave bounces off at many different random angles. Specular reflection occurs if the surface is smooth, with bumps that are small compared to the wavelength of the sound. Diffuse reflection occurs if the bumps on the surface are comparable to the wavelength or larger.

Perspective

If you are used to thinking about the way that sound propagates as a wave, complete with diffraction and interference effects, you may be surprised to find sound waves treated as though they were bouncing balls as they reflect from a surface. Does this mean that the nature of sound has changed somehow? No, sound waves are still waves, and there are precise (but complicated) experimental and theoretical ways to deal with the interaction of these waves with surfaces. But for many practical purposes it is an adequate approximation to imagine a wave as following the path of a projectile like a ball as it reflects (bounces) off a surface. The most important assumption in the approximation is that the surface itself (whether it be smooth or bumpy) is large compared to the wavelength of sound. Because sound wavelengths are often large (4 m for bass notes) it is clear that this assumption requires large surfaces. That is why the bouncing ball (or splattering tomato) approach is used in describing rooms. Rooms are large.

15.2 Transmission Loss

We often have the goal of minimizing sound transmission, for example minimizing the transmission of a conversation from one office to another, or the sound of a television from one apartment to another. Unfortunately, the superb dynamic range of the human hearing process works against efforts to reduce the annoyance of

transmitted sound. Consider that if you succeed in eliminating 99 % of the sound intensity, you have only reduced the level by 20 dB (see Exercise 4). A reduction of only 20 dB may not be enough to eliminate the disturbance caused by unwanted sound, especially if the sound includes information such as speech.

Sound transmission can be reduced by barriers, such as walls. The reduction of transmitted sound intensity by a wall is the *attenuation* of the wall. A wall can attenuate sound in two ways. It can absorb sound and it can reflect sound. Sound is absorbed by a wall when wall surfaces vibrate and convert the energy into heat through friction. Sound is reflected when it comes to an interface between two different media. A double wall works well because there are multiple changes of medium: air, to wall, to air, to second wall, to air again. Upon each reflection there is some absorption, and that eliminates sound. Walls also transmit sound, and therefore fail to some degree, because of holes in the wall (like a gap under a door) and because the walls are caused to vibrate as a whole by the incident sound. To avoid vibration of an entire wall the wall material should be heavy. Lots of mass is the best way to avoid transmission by vibration. Unfortunately it is a costly way to build.

As a general rule, high-frequency sounds are effectively reflected or absorbed by walls, but low-frequency sounds tend to get transmitted. Plotting the attenuation of a wall (in dB) as a function of frequency always leads to a rising curve—more attenuation for higher frequency. Walls can be characterized by sound transmission class (STC) which refers to the attenuation at 500 Hz, an arbitrarily chosen frequency. If a wall has a STC rating of 40 dB, you can expect that it will attenuate a 500-Hz sound by 40 dB. It will likely attenuate a 200-Hz sound by less than 40 dB and will attenuate a 2,000-Hz sound by more than 40 dB.

15.3   Room Acoustics

The subject known as "room acoustics" is concerned with what happens inside the room containing the source and not about what happens outside. Therefore, it involves direct sound and reflected sound. Sound that is not reflected back into the room is of no interest. Whether this sound is absorbed on the walls of the room and turned into heat or is transmitted out of the room through the walls, the room acoustician says that it is "absorbed." (Ultimately, of course, the lost sound *is* absorbed, even if it happens to be transmitted elsewhere first.) For instance, an open window is said to be a perfect absorber because all the sound that hits the window goes out and never returns. Thus, from the point of view of the room acoustician, sound that hits a wall is either reflected or absorbed. If 30 % of the sound power is reflected, then 70 % is said to be absorbed.
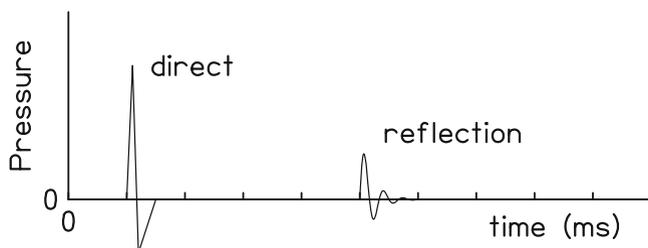
Fig. 15.2 Impulses measured at the position of a listener in a room with a single wall

15.3.1   Early Reflections in a Room

Suppose there is a source, a listener, and a single wall that creates a strong reflection. If the source makes an impulsive sound, like a hand clap at time zero, then there is a brief delay for the direct sound to get to the listener and a longer delay for the reflection (Fig. 15.2).

In a real room with real walls there are multiple early reflections because of single and double reflections from all the walls and other surfaces. Most important for good acoustics is the time gap between the arrival of the direct sound and the arrival of the early reflections. A good listening environment has numerous reflections that arrive with a gap much shorter than 50 ms. Reflections that arrive within the first 20 ms give a sense of intimacy to the acoustical environment. Reflections that come from the side walls give a sense of "surround" or "spaciousness," a desired effect in listening to music. Side wall reflections lead to an incoherence between the sound waves at a listener's left and right ears. The incoherence is responsible for the sense of envelopment—the impression of being "in the sound." Stereophonic sound reproduction has a similar effect in the audio domain. Reflections from the ceiling contribute favorably to the loudness, but they do not lead to the same sense of spaciousness.

Echoes If a strong single reflection arrives more than 50 ms after the direct sound the listener perceives an echo, which is defined as a distinctly heard repetition of the direct sound. Echoes are acoustically bad—really bad. Echoes cause speech to be hard to understand and they cause music to sound "muddy." Even in an environment with lots of other reflections, a particularly intense reflection that is delayed as long as 50 ms can create an echo. Rooms that suffer from an echo must be treated in order to be satisfactory spaces for listening. The location that leads to the offending reflection (usually a back wall) can be covered with absorber. Alternatively, the location can be reshaped to reflect sound over a wide range of angles.
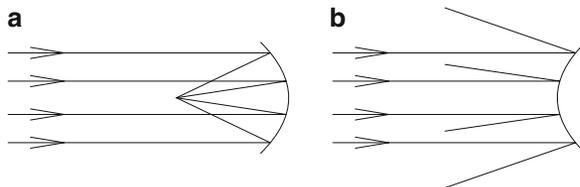
Fig. 15.3 In parts (**a**) and (**b**), sound waves come in from the left and are reflected by a curved surface. In part (**a**) the rays are focused at a point causing the intensity to be large there. In part (**b**) the rays are widely dispersed, helping to create an even distribution of sound intensity

15.3.2   Focused Sound

You know that if sound is reflected from a large, smooth, flat surface, then the sound ray, defining the direction of travel of the wave, bounces off the surface like a ball. Suppose the surface is curved. What then? A concave surface tends to focus sounds as shown in Fig. 15.3a. Concave surfaces are found in cylindrical auditoriums or in rooms with a prominently curved back wall. They occur with domed ceilings as are found in many ceremonial spaces. In extreme cases concave surfaces create whispering galleries, where two people can communicate over amazingly long distances because the vocal waves that are emitted in all directions end up being focused at the location of the listener.

Apart from the fun of whispering galleries, focused sound is normally a bad thing. Focusing of sound can make a delayed reflection strong enough to be heard as an echo. Even if the focused sound is not delayed long enough to create an echo, the focusing concentrates sound power at particular location(s) in the room, while inevitably depriving other locations of power. For good room acoustics, one would prefer that sound power be evenly distributed throughout the room. Even distribution is actually promoted by convex surfaces, which scatter sound waves as shown in Fig. 15.3b. Along with bumpy surfaces, convex surfaces are normally a helpful addition to good sound distribution in a room.

15.3.3   Reverberation

In an ordinary room, sound is reflected from all the surfaces. It is reflected and re-reflected and re-reflected again. After awhile there are so many reflections that it becomes pointless to keep track of individual reflections and where they come from. These reflections come in a dense mass that is called "reverberation." Reverberation is the primary consideration for rooms that are especially designed for listening, and the most important acoustical specification for a room is the *reverberation time*. The reverberation time is the length of time that a tone persists in room after the source has been turned off.
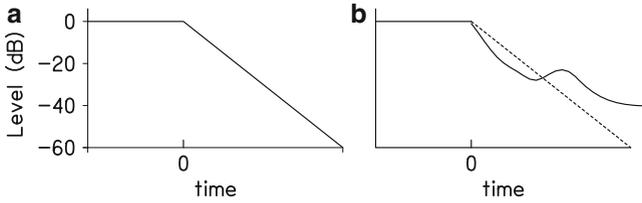
Fig. 15.4 (**a**) To measure the reverberation time we turn off a tone and measure the time that it takes for the sound to fade away by 60 dB as shown by the idealization in (**a**). That time is T_{60}. In the less-than-ideal conditions shown in (**b**) there are two problems. First, the decay is not uniform; second, we can only measure about 40-dB until we reach the noise background. To find T_{60} we use the data we have and estimate the best straight line (shown *dashed*) down 60 dB

The reverberation time is determined by a simple experiment. A tone, with frequency f, is turned on and allowed to fill the room. Then the tone is abruptly turned off. The tone will then decay away and the experimenter measures the time that it takes for the tone to decay by 60 dB. That time is the reverberation time, called T_{60}, at frequency f. The choice of 60 dB is a somewhat arbitrary standard, but it corresponds rather well with our subjective impression of the duration of the decay (Fig. 15.4).

The Sabine Equation It is possible to estimate the reverberation time based on a few simple physical properties of the room. (1) The reverberation time is shorter if there is a lot of absorption in the room, especially on the walls and other surfaces. The greater the absorption, the faster the room loses sound intensity. (2) The reverberation time is longer if the room is larger because sound has to travel further before it can be absorbed on the room surfaces. These two ideas about reverberation time form the basis of the Sabine equation,

$$T_{60} = 0.16\, V/(A_T). \tag{15.1}$$

Here, T_{60} is the reverberation time in seconds, V is the volume of the room in cubic meters, and A_T is the total absorbing area in square meters. The number 0.16 has units of seconds per meter. It has to account for the fact that the quantity $V/(A_T)$ on the right-hand side of the equation has dimensions of length (meters) and the left-hand side has dimensions of time (seconds). This numerical value (0.16) would be different for a calculation done in English units of volume and absorbing area or for a different reverberation time such as T_{30}.

The volume of the room (V) is a simple concept. If the room is rectangular the volume is just the length times the width times the height. The total absorbing area (A_T) needs some discussion. The A_T is the sum of all the absorbing surface areas in the room. To find an absorbing surface area, you start with the area itself (A), measured in square meters, and multiply by the absorption coefficient (α) for the surface material. Absorption coefficients depend on the material and they depend on frequency too. That is why the reverberation time depends on frequency.

Your intuition already tells you something about absorption coefficients. Suppose a high-frequency tone (e.g. 2,000 Hz) encounters heavy draperies. You expect that a lot of that sound will be absorbed. Therefore it does not surprise you to learn that the absorption coefficient at 2,000 Hz for heavy drapes is 0.70, meaning that 70 % of the sound power will be absorbed. At the other end of the scale, you expect that glazed tile reflects most of the incident sound and you are not surprised to learn that the absorption coefficient is about 0.01, meaning that only 1 % of the incident sound intensity is absorbed. Absorption coefficients can be found in the table at the end of the chapter.

Calculating Reverberation Time The difficult part of Eq. (15.1) is the total absorbing area, A_T. Mathematically, we say that the total absorbing area is a sum of surface areas times their absorption coefficients plus the sum of the effective absorbing areas (EA) attributed to individual objects like chairs or persons.

$$A_T = \sum_{surfaces} A_{surface} \alpha_{surface} + \sum_{objects} EA_{objects} \qquad (15.2)$$

For example, if a room has four walls, each with an area of $100 \, \text{m}^2$ and an absorption coefficient of 0.3, and a floor and ceiling, each with an area of $400 \, \text{m}^2$ and an absorption coefficient of 0.1, then the sum over surfaces is $4 \times 100 \times 0.3 + 2 \times 400 \times 0.1$. That sum is $200 \, \text{m}^2$. If this room is occupied by 40 adult persons then the absorbing area is increased by 40 times the effective area of a person. From the last entry in the Table of Absorption Coefficients we see that the effective absorbing area of a person (at 500 Hz) is $0.45 \, \text{m}^2$. Thus, the sum of objects is 40×0.45 or 18, and in the end $A_T = 218 \, \text{m}^2$.

Reverberation and Intensity in a Large Room There is a useful analogy to sound and its reverberation in rooms, namely a stream of water from a hose trying to fill a leaky bucket. The stream of water represents the source of sound. The bucket represents the room, and the leak is the absorption. If the stream of water flowing into the bucket suddenly stops, it takes a while for all the water to leak out of the bucket. The time to drain the bucket is analogous to the reverberation time.

This analogy can go further. Suppose that all the holes in the bucket are somehow plugged up. Then, a continuing steady stream of water into the bucket will cause the level to rise indefinitely. Similarly, if it were somehow possible to eliminate all the absorption in a room, the sound intensity would grow without limit. Eventually the sound would be intense enough to destroy the walls.

In a physically reasonable case, it is not possible to eliminate all the absorption. The correct analogy to realistic absorption is to imagine that the leaky bucket has holes punched up the sides. The higher the water level the greater the flow of water leaking out. What happens then is that the level of water in the bucket will rise until it reaches a steady state where the rate of water flow from the hose is equal to the rate of water flow out all the leaks. Similarly, the level of sound in a room will grow until the rate of sound absorption is equal to the power of the source. As a result,

rooms with little absorption are "loud" rooms. The intensity of a steady-state sound in a room from a source with power P is given by

$$I = 4\,P/A_T. \tag{15.3}$$

You will notice that this formula for intensity does not include any information about the distance to the source. The formula calculates the intensity in the *reverberant field*, measured at places that are far enough away from the source that the intensity is dominated by reverberated sound and not by direct sound.

Because excessive reverberation makes speech hard to understand, you might imagine that the ideal classroom or auditorium intended only for speech would have no reverberation at all, i.e., the reverberation time would be zero. By aggressive use of absorbers (carpet on the floor, acoustical tile on the ceiling, and sound-absorbing panels on the walls) it is possible to reduce the reverberant sound to a very small level. However, too much absorption leads to the problem of inadequate intensity. For a room seating more than 100 persons, a talker needs reflections from the surfaces of the room to be heard clearly. In the end, when designing a room for speech comprehension a designer cannot simply apply absorption mindlessly. There is no substitute for good judgement.

Recommended Reverberation Times

- For classrooms and other environments where it is important to hear speech clearly, T_{60} should be about 0.5 s.
- For baroque concertos or small jazz ensembles where it is important to hear inner voices, T_{60} should be about 1.5 s.
- For romantic music where the goal is emotional drama, T_{60} should be between 1.9 and 2.2 s.
- To produce the big sound of an organ in a church T_{60} should be 2.5 or greater. A vast cathedral may have a reverberation time as long as 9 s.

15.4   Gaining Control of Acoustical Spaces

When a new concert hall or major theater opens in a community, it is a time of great local interest and pride. It is also a time of anxiety. How will the new hall sound? Will speech be comprehensible? Will music be rich and exciting? The developers or the community have raised millions of dollars to build the hall. Will it work as intended?

You might think that the acoustical design of a hall ought to be a sure thing. After all, the Sabine equation has been known for many years and the absorbing characteristics of materials are well known. There should be no problem with getting the reverberation times right at low, mid, and high frequencies. However, there are other details, especially in the early reflections, that are critical to the

success of a good hall. Early reflections have to arrive with the correct delays following the direct sound and with the right density. The balance between low-frequency early reflections and high-frequency early reflections needs to be correct to produce a "warm" sound. It is important that adequate early reflections come from the side walls to establish a sense of envelopment.

In recent years, acoustical consultants have begun to model large and expensive halls on computers as part of the design process. The computer models assume a source (e.g., a piano) on stage and a listener's position somewhere in the audience area. The goal of a computer model is to calculate the transmission of sound from source to receiver and actually let a listener, wearing headphones, hear a simulation of the hall as it is designed. To do that calculation the computer needs a lot of data consisting of the exact location and size of each reflecting interior surface. This information can be taken from architectural drawings. The computer also needs data on the absorption coefficients of the materials chosen by the architect. Once it has all the data, the computer goes to work, calculating thousands and thousands of reflections of the synthetic piano sound. The end result allows a person to put on headphones and hear the sound of a piano being played in the hall before ground is broken for construction. It is obviously easier and cheaper to make changes sooner rather than later. How well does this computer simulation process work? At this point, it is probably too early to say. The technique is still being evaluated. What can be said is that the number of halls that have opened with serious acoustical problems has been less in recent years, compared with only a few decades ago.

Absorption coefficients of materials

Material	125 Hz	500 Hz	2,000 Hz
Acoustical plaster	0.15	0.50	0.70
Acoustical tile	0.20	0.65	0.65
Brick wall—unpainted	0.02	0.03	0.05
Heavy carpet on heavy pad	0.10	0.60	0.65
Light carpet without pad	0.08	0.20	0.60
Concrete—painted	0.01	0.01	0.02
Concrete—unpainted	0.01	0.02	0.02
Heavy draperies	0.15	0.55	0.70
Light draperies	0.03	0.15	0.40
Fiberglass blanket (2.5 cm thick)	0.30	0.70	0.80
Fiberglass blanket (7.5 cm thick)	0.60	0.95	0.80
Glazed tile	0.01	0.01	0.02
Paneling (0.15 cm thick)[a]	0.10	0.20	0.06
Paneling (0.30 cm thick)[a]	0.30	0.10	0.08
Plaster	0.04	0.05	0.05
Vinyl floor on concrete	0.02	0.03	0.04
Wood floor	0.06	0.06	0.06

[a]Plywood paneling supported at 1 m intervals and backed with 5 cm air space

Absorbing areas (m^2)

Object	125 Hz	500 Hz	2,000 Hz
Adult person	0.30	0.45	0.55
Heavily upholstered theater seat	0.33	0.33	0.33

Exercises

Exercise 1, Something there is that doesn't like a wall

Standard home wall construction consists of dry-wall panels mounted on two-by-four studs. Explain the mechanisms of sound transmission through such a wall. How can sound transmission be reduced? Does it help to fill the wall with fiberglass insulation?

Exercise 2, Bad rooms

Think about bad acoustical environments you have experienced. What do you think made them bad?

Exercise 3, Confronting brick walls

You are on a committee to design a new auditorium. Your colleague argues that using a brick interior wall would be preferable to using a plaster wall because the brick wall is rough and will lead to diffuse reflection. Diffuse reflection is desirable in an auditorium. What is your opinion of this argument?

Exercise 4, Decibels once again

The text says that by reducing the sound intensity by 99 % you reduce the sound level by 20 dB. Prove that this statement is true.

Exercise 5, All energy ultimately turns into heat

The text says that the ultimate fate of all energy is to be turned into heat. Is that really true. How about nuclear energy? Would that be an exception?

Exercise 6, Practice with the Sabine equation

In the text, Eq. (15.2) was illustrated with a room having a total absorbing area of 218 m^2. Suppose that the volume of the room is 2,000 m^3. Continue the calculation to show that the reverberation time is $RT_{60} = 1.5$ s.

Exercise 7, More practice with the Sabine equation

Find the reverberation time at 500 Hz of a rectangular room with dimensions 6.3 m by 7.7 m by 3.6 m high, where the walls and ceiling are plaster and the floor is vinyl on concrete. Use the Table of Absorption Coefficients at the end of the chapter.

Exercise 8, Everyone's alternative to Carnegie Hall

Estimate the reverberation time of a shower stall. [Hint Estimate the dimensions of a shower stall and assume that all the surfaces have absorption coefficients similar to glazed tile.]

Exercise 9, Sabine fails for dead rooms

Prove that the Sabine equation fails when absorption coefficients are very high. Hint: Consider the reverberation time when absorption coefficients are 1. Then 100 % of the sound ought to be absorbed.

Exercise 10, Unit analysis

The text says that the quantity $V/(A_T)$ has dimensions of meters. Explain why this is so.

Exercise 11, Expanding the room

Consider two rooms, A and B. The surfaces of room B are made of the same materials as the corresponding surfaces of room A. Thus, the rooms are identical except that every dimension (length, width, height) of room B is twice as long as the corresponding dimension in room A. Compare the reverberation times of rooms B and A.

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