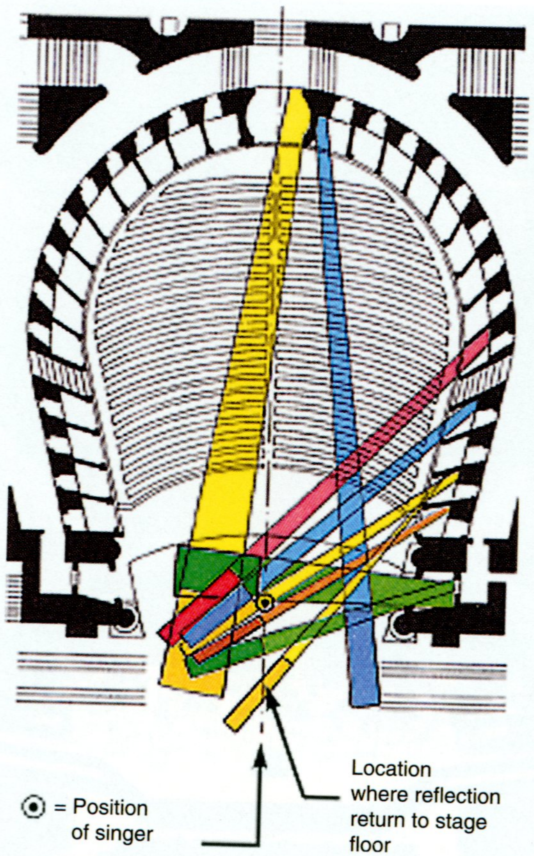
Colour Plate 8



Chapter 6 Fig. 6.21 Reflections, originating from a singer, returning to the stage, in the Teatro San Carlo, Naples (after Weisse and Gelies, 1979)

Chapter 5
Foundations of Room Acoustics

5.1 Reflection and Refraction

5.1.1 Reflection from a Flat Surface

Inasmuch as sound propagates in a straight line in a homogeneous medium, as is the case for air at rest at uniform temperature, the presentation of a sound ray, which connects the sound source and the observer in a straight line, is well suited for a number of acoustical considerations. It forms a visual foundation for a geometrical point of view of sound propagation in a room.

When a sound ray impinges on a sufficiently large flat surface, it is reflected. The well-known law of optics, that the angle of incidence is equal to the angle of reflection, goes into effect. This is a phenomenon which has its cause in the wave nature of sound or light respectively. Furthermore, the incident ray, reflected ray and a line perpendicular to the wall at the contact point lie in the same plane. This reflection process is represented schematically in Fig. 5.1a. This illustrates clearly that the angle between the incident and reflected ray depends on the incident angle, thus, by appropriate orientation of the surface, the incoming ray can be reflected into any desired direction.

When two walls are perpendicular to each other the incident sound is reflected twice. It always leaves the corner in the direction exactly opposite to the incident direction. This case is illustrated in Fig. 5.1b. From the two indicated ray paths it is noted that, in contrast to simple reflection from one plane, the direction of the reflected ray depends only on the direction of incidence of the incoming sound.

If two walls in contrast, form an obtuse angle, a single reflection results for steep incidence. For shallow incidence, double reflection results in the corner. Both possibilities are represented in Fig. 5.1c for the case that the sound initially impinges on the lower wall. The second reflection of the sound ray represented by the broken line leads to a direction which is relatively flat in relation to the left wall. When considering, that this secondary reflection can only become steeper when the incident ray on the right becomes even shallower one recognizes that there is a limiting case for double reflection when the incoming sound ray is parallel to

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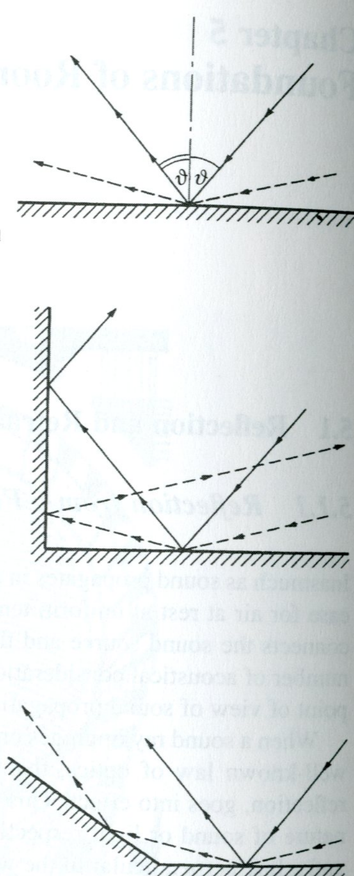


Fig. 5.1 Reflections from a flat surface

the wall. The consequence is that for an obtuse corner, in a certain region near the angular bisector, there are no secondary reflections.

5.1.2 Reflection from Curved Surfaces

When sound falls on a large wall with a curved surface, it will be reflected according to the angle of incidence of the ray, in the plane tangential to the curve at the point of contact, where again the incidence ray, the reflected ray, and the normal to the tangential plane, all lie in the same plane. Depending on the distance of the sound source from the wall and the radius of curvature, focusing or spreading effects can occur in analogy to optical curved mirrors. The most important cases are represented in Fig. 5.2:

(a) If the distance from the sound source to the wall is greater than half the radius of curvature, a focusing point beyond the center of curvature is formed. If the

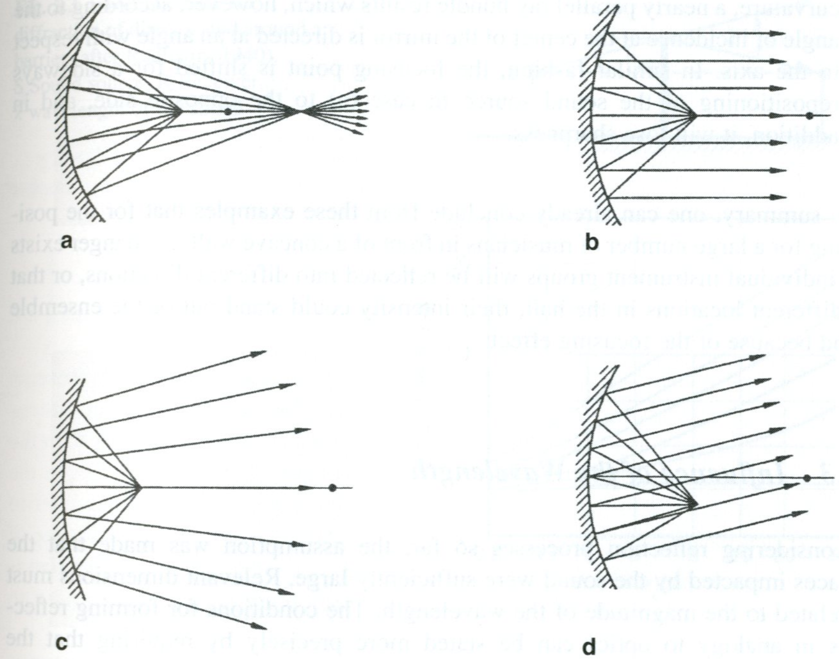


Fig. 5.2 Reflection from curved surfaces

sound source, as drawn, lies between the center of curvature and the wall, then the point of focus is located at a greater distance. Such sound energy concentration is perceived as detrimental when the focusing point falls within a region of the audience. It is, however, perceived as advantageous when the sound is to be focused onto a microphone by a ellipsoidal mirror (for example, such an arrangement has found long time use in the "Marktkirche" in Hannover, prior to the development of technically superior micro-port arrangements).

(b) When the distance of the sound source to the wall is equal to half the radius of curvature, a parallel ray bundle in the direction of the axis of the reflector is generated. A parabolic mirror is the most favorable shape to take advantage of this effect. Fig. 5.2d, however, can also be interpreted in the inverse direction: When a parallel ray bundle, i.e., sound from a far distance source falls on a hollow curve, a focal point is created at a distance corresponding to half the radius of curvature.

(c) When the source to wall distance is smaller than half the radius of curvature, the reflected sound rays spread as though they came from a single point behind the wall. Such a broadening of the sound field can occasionally be advantageous for uniform energy distribution over a certain angular region. Similarly, convex curvatures can lead to a fanning of an incoming ray bundle.

(d) When the sound source is not located on the axis of the reflector, then, for a parabolic mirror, for a source to wall distance equal to half the radius of curvature, a nearly parallel ray bundle results which, however, according to the angle of incidence at the center of the mirror is directed at an angle with respect to the axis. In similar fashion, the focusing point is shifted for a sideways repositioning of the sound source in case (a) to the opposite side, and in addition, it will lose sharpness.

In summary, one can already conclude from these examples that for the positioning for a large number of musicians in front of a concave wall, the danger exists that individual instrument groups will be reflected into different directions, or that for different locations in the hall, their intensity could stand out of the ensemble sound because of the focusing effect.

5.1.3 *Influence of the Wavelength*

In considering reflection processes so far, the assumption was made that the surfaces impacted by the sound were sufficiently large. Relevant dimensions must be related to the magnitude of the wavelength. The conditions for forming reflections in analogy to optics can be stated more precisely by requiring that the dimensions of sound obstacles must be at least several wavelengths. Otherwise, the sound is bent around the obstacle and hardly reflected. Thus, a wall of dimensions comparable to three wavelengths, presents only a short sound shadow and elements of the size of one wavelength practically do not disturb the sound field at all. Inasmuch as the relationship of the geometric dimensions relative to wavelength depends on frequency, the acoustic effect of reflectors or sound barriers changes with pitch. Low frequency contributions, i.e., components with long wavelengths, can still be heard strongly even when the sound source is hidden from view. High tones, however, are even reflected by small objects.

The shadowing effect of obstacles between sound source and listener can be quantitatively determined on the basis of Fig. 5.3. If a wall is located between sound source and listener, as for example the partition of the orchestra pit in the opera house, then, on the one hand, the angle with which the sound ray is bent at the edge is important. On the other hand, the effective height with reference to the straight-line connection between sound source and listener plays a role, more exactly, the relation of this height to the wavelength. It is noteworthy that already for an angle of 0°, i.e., a just possible sight connection, an attenuation of from 5 to 6 dB occurs. This is understandable when one considers that by the diffraction a part of the sound energy is bent into those regions behind the barrier which would not receive any sound energy without refraction. It is further noteworthy, that the degree of shadowing even for small angles varies strongly, that however, between 30 and 90°, there is relatively little change.

Inasmuch as in practice, frequently individual free-standing or hung reflectors are used, the question naturally becomes of interest: Above which frequencies do

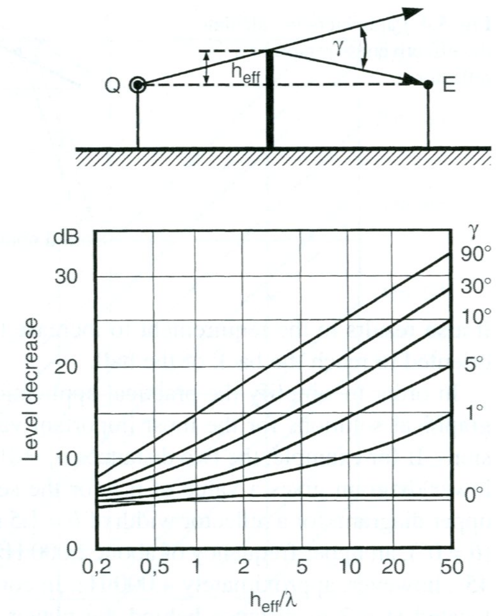


Fig. 5.3 Level decrease for diffraction of direct sound around a barrier (after Redfearn, 1940). S Sound source, R Receiver, λ wavelength of the sound

they reflect effectively? As sketched in Fig. 5.4, if the distance from the sound source to the middle of the reflector is designated as a_1, the distance from listener as a_2, the width of the reflector in the observed plane with b and the angle of incidence as θ, then wave theoretical considerations concerning the effectiveness of reflectors give a lower frequency limit as

$$f_u = \frac{2c}{(\mathrm{b}\ .\ \cos\theta)^2} \cdot \frac{\mathrm{a}_1\ .\ \mathrm{a}_2}{\mathrm{a}_1 + \mathrm{a}_2}$$

In this equation, c is the speed of sound in air. Furthermore, the condition must be satisfied that the distances a_1 and a_2 are larger than the reflector width b (Cremer, 1953). Below this limiting frequency, the level of reflective sound drops with 6 dB per octave (Rindel, 1992).

This formula indicates that the regions of reflector effectiveness reaches increasingly lower frequencies as:

Reflector size increases
Distance to the sound source decreases
Distance to the listener decreases
The sound falls more steeply onto the reflector

This means that seats located far back in the hall will receive fewer low frequency contributions than the front rows when all reflectors are of equal size.

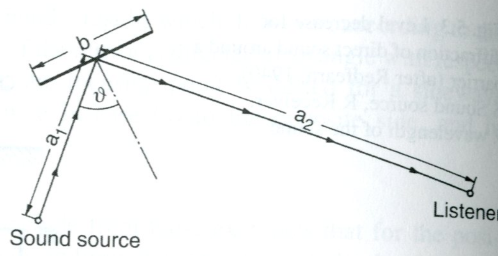


Fig. 5.4 Parameters to calculate the effectiveness region of a reflector

It also results in the requirement to increase the size of those reflectors which are oriented to reach the back of the hall.

In order to simplify the practical application of this equation, Fig. 5.5 presents graphical solutions for the most important variation regions of individual dimensions. If for example, the two distances $a_1 = 10$ m and $a_2 = 20$ m are given, then the lower diagram gives a value of 6.7 for the second term of the formula. From the upper diagram, for a reflector width of $b = 1.5$ m and perpendicular sound incidence ($\theta = 0°$), an upper frequency of about 2,000 Hz is relevant, for a sound incidence of 45°, however, approximately 4,000 Hz. In contrast, if a reflector of 2×2 m size is located at a 2 m distance behind the player, the effective region is increased to include frequencies below 300 Hz.

Aside from the size of the reflector, its mass also plays a role for its effectiveness. Plates (or foils) which are too light transmit a portion of the sound energy, or they themselves vibrate too strongly. A desirable area weight of at least 10 kg m^{-2} for reflectors of mid and high-frequencies can be used as an initial point of reference, this corresponds approximately to a 12 mm wood plate. This requirement is especially relevant for reflectors of speech and singing. If frequencies of the bass region also need to be reflected, approximately 40 kg m^{-2} are required.

The previous considerations dealing with reflection relationships were relevant for smooth, i.e., unstructured reflection surfaces. Frequently, however, wall and ceiling surfaces are structured by small protruding or receding surfaces or added profiles. Such surfaces can have a scattering effect, i.e., instead of the previously described geometric reflection of the sound waves (in one direction), the sound energy is reflected diffusely in all directions. This effect is most strongly pronounced when the depth of the structure is of the order of magnitude of one-fourth to one-half of a wavelength. The frequency region for diffuse reflection can be broadened by a differential depth arrangement of the wall structure. Staggering, according to principles of certain probabilistic sequences of whole numbers, according to elementary number theory, or so-called maximal sequences, are particularly advantageous (Schroeder, 1979).

Below the frequency regions for diffuse reflection, i.e., for larger wavelengths, the structured surface behaves like a smooth wall; i.e., geometric reflection occurs. Above the frequency regions for diffuse reflection, the individual surfaces of the structure act as geometric reflection surfaces and angular mirrors. This can certainly result in reflection directions other than those corresponding to the main orientation

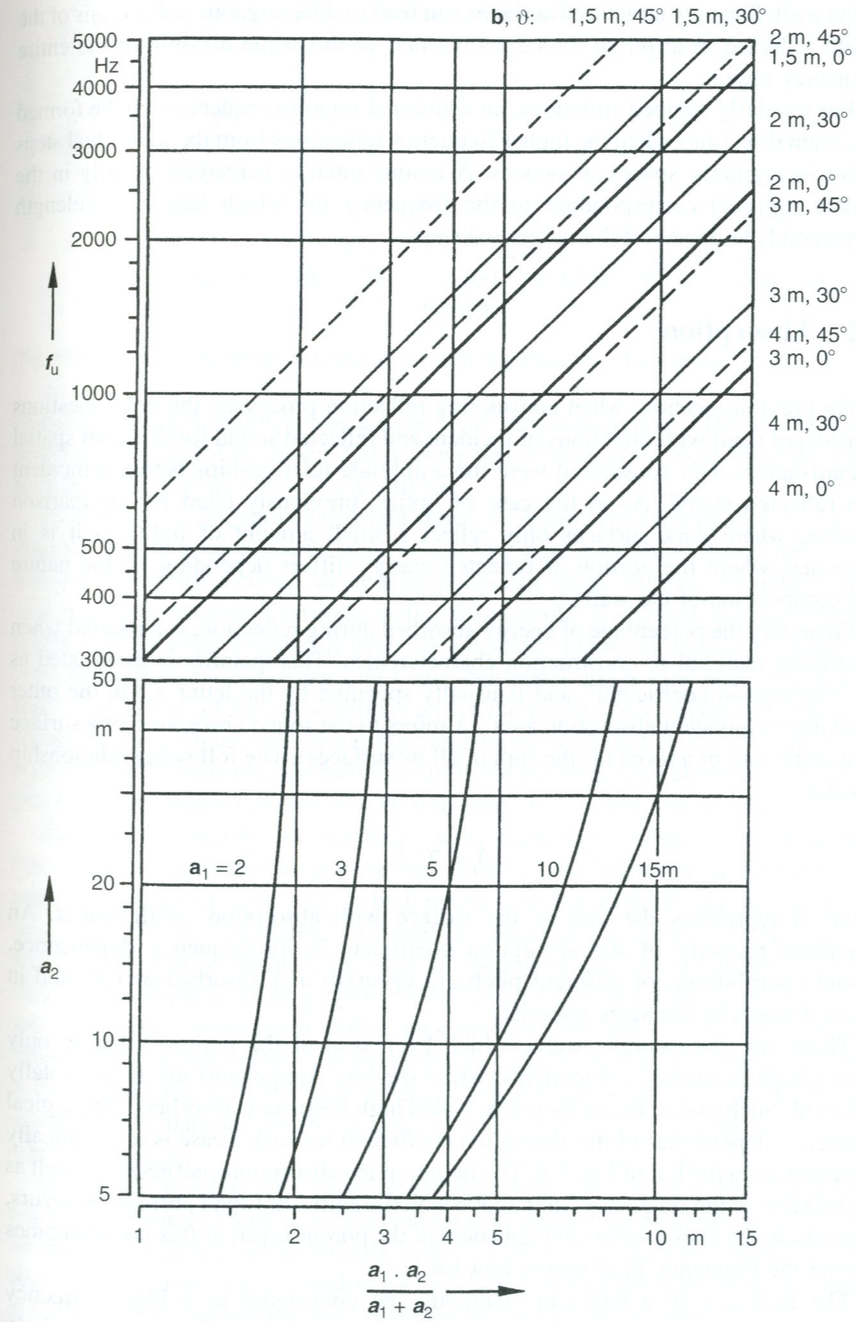


Fig. 5.5 Diagrams for the determination of the lower frequency limit of a reflector. Values for f_u, corresponding to given values for the reflector width (b) and the angle of incidence (θ), are obtained by starting from a given distance a_2 at the left edge on the bottom diagram and going to the curve of known distance a_1, and proceeding vertically upward from that point of intersection to the straight line on the upper diagram corresponding to the given values of b and θ. f_u can then be read from the left edge of the upper diagram

of the wall. Strongly structured surfaces can lead to differing tone colorations of the sound reflected in different directions because of this triple division of the entire frequency region.

For regularly stepped structures, an additional impulse sequence may be formed in certain directions when the higher frequency reflections from the individual steps arrive in regularly spaces sequences. A unique pitch is perceived (mostly in the middle register) corresponding to the frequency for which half a wavelength corresponds to depths of the individual steps.

5.2 Absorption

In the previous section, when considering reflection processes, the only questions considered dealt with directions of incident and reflected sound for different spatial circumstances. Not considered were the amplitude relationships between incident and reflected sound. As in the case of optics, previously cited for comparison reasons, where dark surfaces only reflect a small amount of light, so it is in acoustics, where the portion of reflected energy differs depending on the nature and composition of the walls.

Generally the percentage of energy absorbed during reflection, is indicated when describing material or construction characteristics. This quantity is designated as the "absorption coefficient" and is usually specified by the letter α. On the other hand the "equivalent absorption area" A refers to the sound absorption of a surface of specific size or a room (as the sum of all its surfaces). The following relationship is valid

$$A = \alpha \cdot S$$

where S represents the size of the surface with absorption coefficient α. An important property of the absorption coefficient is its frequency dependence. Sound contributions of different pitch are generally not absorbed or reflected in equal strength by the same material.

There are, for example walls, which by reason of the porous structure only absorb high frequency components, while the low components are nearly totally reflected. Such materials are therefore called high frequency absorbers. The typical frequency dependence of the absorption coefficient for such a case is schematically represented on the left of Fig. 5.6. The height of the absorption coefficient as well as the location of the frequency limit above which significant sound absorption occurs, depends on the composition and thickness of the porous layer: as this layer becomes thinner the frequency limit moves upward.

The audience in a hall can essentially be considered as a high frequency absorber. Thus the audience absorbs all sound contributions from approximately 500 Hz on upwards. In this, the surface occupied by the audience is a determining factor, while the seating density is only of subordinate significance. This means that the same number of persons affect a higher degree of absorption when distributed over a larger surface. For example, 200 persons distributed over an area of 100 m^2

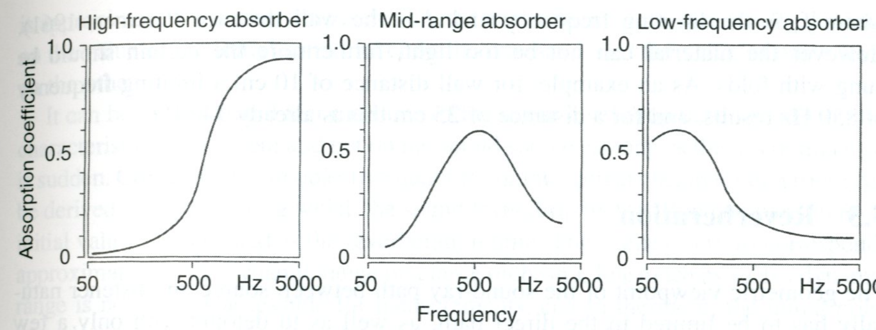


Fig. 5.6 Degree of absorption of materials for differing frequency dependence

possess an equivalent absorption area of 95 m^2 at a frequency of 1,000 Hz. However when they are distributed over 200 or even 300 m^2 their equivalent absorption area rises to above 140 or 165 m^2 respectively.

In contrast, the diagram on the right shows the typical behavior of a low frequency absorber which predominantly absorbs the low tone contributions and reflects the high ones. This effect comes about when plates can vibrate in front of a hollow space as is most often the case for wood paneling for example. As the hollow space becomes deeper and the plate becomes heavier the frequency region of maximum absorption moves toward lower frequencies. For very thin plates and hollow spaces of shallow depth, and above all for constructions where the hollow space opens into the room through slits or holes, the absorption maximum is shifted toward the region of intermediate frequencies, one therefore speaks of midfrequency absorbers. The effective frequency region can thus also be influenced by construction techniques.

There are virtually no materials with frequency independent absorption. The only ones worth mentioning are the "sound – hard" materials such as concrete, marble, or plastered stone walls, which reflect sound of all pitch regions with nearly no attenuation. In this context, however, it should be mentioned that an organ, in reference to its front surface, provides an absorption coefficient between 0.55 and 0.60 in the entire frequency range from 125 to 4,000 Hz. Deviations from this, determined by construction differences are relevant only for low frequencies (Meyer, 1976; Graner, 1988). In concert halls or radio studios it can be meaningful, in individual cases to consider covering the organ while not in use when a reflecting surface rather than an absorbing one is desirable for the orchestra sound at the relevant location.

In practice, curtains are a particularly interesting case, because they can be used without structural changes, or as a temporary proviso. As a porous material, they absorb, as do carpets, preferentially high frequency contributions. However, their absorption regions can be broadened to include lower frequencies when suspended at certain distances from the wall. A somewhat uniform absorption results above the frequency for which the wall distance amounts to one-fourth of the wavelength. From this condition the following formula can be derived

$$f_u = 8{,}500/d \quad f_u \text{ in Hz}, d \text{ in cm},$$

where f_u is the limiting frequency and d is the wall distance (Cremer, 1961). However the material can not be too light, furthermore the curtain should be hung with folds. As an example, for wall distance of 10 cm a limiting frequency of 850 Hz results, and for a distance of 25 cm this is already 340 Hz.

5.3 Reverberation

The geometric viewpoint of the sound-ray path between source and listener naturally has to be limited to the direct path, as well as to detours with only a few reflections, because otherwise the process becomes too cumbersome and visually complex. In order to include all reflection processes to the point of complete absorption, and at the same time describe, if possible, relationships at all points of the room, statistical methods become necessary. For consideration of sound processes after turning off the sound source, it becomes particularly advantageous to include all reflections: The sound reflections arrive at the listener in an increasingly dense time sequence and thus they shape the reverberation in slowly decreasing intensity.

A typical level progress is represented in Fig. 5.7 for such a case. After turning the sound source off, the level (in logarithmic dB scale) decreases approximately linearly with small variations, until it merges with the ambient noise level in the room. In that context it is irrelevant for the basic shape of the curve whether the concern is with the stopping of an electroacoustic sound source or the termination of an orchestral chord. The listener can follow this reverberation until it is submerged in the noise level. In the graphically represented example this

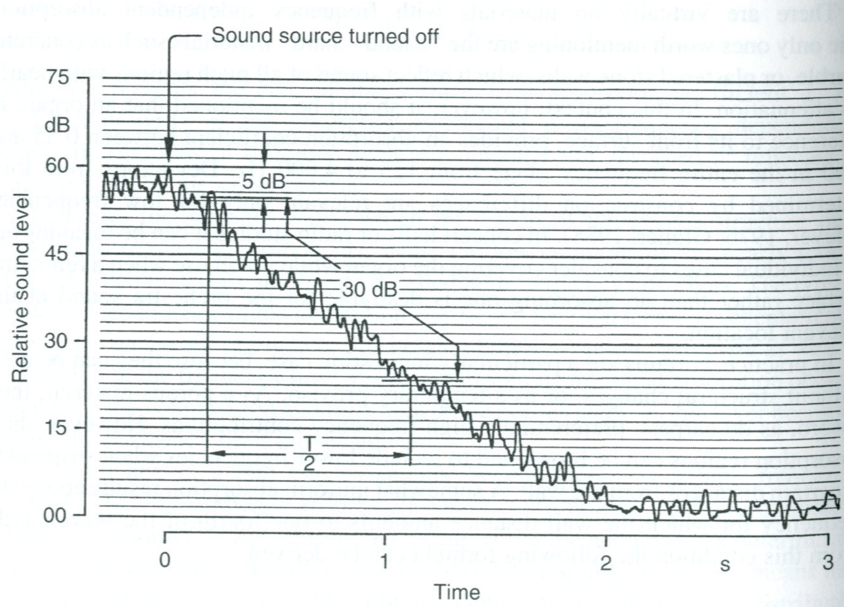


Fig. 5.7 Sound level during a reverberation process

is approximately 2 s. This time is designated as the decay time. It naturally depends on the value of the initial sound level on the one hand, and the value of noise level on the other.

It can be demonstrated that the slope of the linear level drop depends only on the characteristics of the room and not on the sound source, as long as the discontinuation is sudden. Consequently an objective quantity for the acoustic behavior of a room can be derived: the time during which the sound level drop by 60 dB in comparison to its initial value is designated as the reverberation time. This value of 60 dB corresponds approximately to the dynamic range of a large orchestra. Inasmuch as such a dynamic range is not always accessible for measurements, and furthermore, the initial point often is not uniquely recognizable, the following procedure has been specified for the determination of reverberation times: starting with a drop of 30 dB from a value of 5 dB below the steady level, the measured time is doubled. This method is indicated in Fig. 5.7. From the graphically represented level drop a reverberation time of approximately $2 \times 0.9 = 1.8$ s is obtained.

In the course of a musical performance, the temporal note sequence and the actually dynamic structure rarely provides a drop of 60 dB. Consequently, particular attention is given to the beginning portion of the decay curve. A slope of the first 10–20 dB is determined, and from that, the time for a uniform level drop of 60 dB is calculated. For an evaluation of the first 10 dB one speaks of the "Early-Decay-Time" (Jordan, 1968), for the first 15 dB the "Initial-Reverberation-Time" (Atal et al., 1965) and for 20 dB "Beginning-Reverberation-Time" (Kürer and Kurze, 1967).

The reverberation time of a room decreases as individual reflections become weaker, i.e., the stronger the walls, the floor, and the ceiling, etc. absorb sound. In contrast it becomes longer for increased time separations between individual reflection processes; this "free path length" increases with the size of the room. When the total absorption of the room is not too large, these relations are represented by the Sabine reverberation formula:

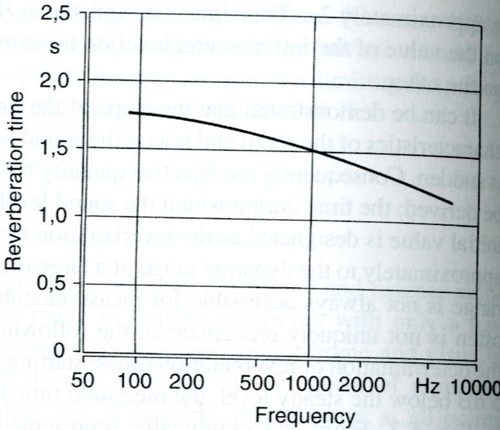
$$T = 0.163\ V/A \quad T \text{ in s},\ V \text{ in m}^3,\ A \text{ in m}^2,$$

where T is the "Sabine" reverberation time (corresponding to the 60 dB definition), V is the volume of the room and A is its equivalent absorption area which is calculated from the sum of the A values of the individual surfaces and objects.

Inasmuch as absorption is frequency dependent, the reverberation time also shows a frequency dependence, which, depending on the nature and furnishings of the room, can exhibit rather differing characteristics. As an example for a reverberation curve, the reverberation time of the fully occupied Bayreuth Festspielhaus is represented in Fig. 5.8. It is noted that the reverberation time for low frequencies is longest and decreases for the higher registers. It should further be noted that for high frequencies, an attenuation occurs during sound spreading (dissipation loss) in addition to the absorption at the walls as described.

The frequency dependence of the reverberation time is of great importance for the auditory tonal impression, since it causes a tone color change during the decay.

Fig. 5.8 Reverberation curve of the Bayreuth Festspielhaus under fully occupied conditions (after Beranek, 1962)



The faster the high components lose in intensity, the duller the decay process, as caused by the room. However, consideration must be given to the fact that in a certain sense the rise in the reverberation time below 125 Hz finds compensation in the characteristics of the ear. Since the "equal loudness curves" (see Fig. 1.1) are more closely spaced at those frequencies, a region of 60 phons is traversed by a level range of less than 60 dB so that a reverberation process at low frequencies appears shorter than an equally steep level drop at higher frequencies.

The early time decay in the region from 125 to 2,000 Hz has proven particularly suitable for characterizing the influence of a room on tone color (Lehnmann, 1976). This is because the dynamic short-time structure of music occupies a region of relatively narrow level difference. The Early-Decay-Time for most rooms is somewhat shorter than the Sabine reverberation time, particularly at low frequencies, when coupled room sections – e.g., above ceiling reflectors- contribute to late reverberations.

When evaluating reverberation curves of different rooms it becomes of interest to determine which smallest variations in the reverberation time are discernable for the trained ear. In a simplified approach this question can be answered as follows: for short reverberation times below 0.8 s, steps of approximately 0.02 s are noticeable, while the sensitivity above this limit amounts to approximately 3.5% of the relevant reverberation time (Seraphim, 1958). In practice, this means that values need not be specified more accurately than 0.1 s.

5.4 Direct Sound and Diffuse Field

5.4.1 The Energy Density

When a sound source radiates a long tone or a continuing sound, the direct sound and the multiplicity of sound reflections arrive at the listener at the same point and