8 – Room and Auditorium Acoustics

Acoustical properties of rooms and concert halls are mainly determined by the <u>echo</u> that depends on the <u>reflection</u> and <u>absorption</u> of sound by the walls. <u>Diffraction</u> of sound also plays a significant role in the room acoustics. In contrast to the sound in a free space, intensity of which decreases according to the <u>inverse square law</u>, $I \propto 1/r^2$, the sound in a room consists of a <u>direct sound</u> and the <u>reflected sound</u>, so that the full sound intensity does not decrease so fast with the distance from the source. This is why the acoustics in well-build halls is much better than in the free space (like in open-air concerts). In good concert halls one can hear the music well at any place, even in the back.

In principle, acoustics of any room can be calculated but it is difficult to do for a room of a complicated shape with a lot of architectural details. Also the audience plays a significant role in the absorption of sound and its effect is difficult to take into account theoretically. So in many cases experimenting with acoustics is very useful.

The problem simplifies much for simple shapes such as rectangular and spherical. There are programs simulating the acoustics of rectangular rooms that can be used to improve sounding of music recordings.

On the other hand, general principles of building good concert halls without a full acoustical calculation are well known. Still, architects continue to make mistakes in the acoustical design, so that hall architecture can be considered as an art, not only a science.

• Avoid round walls (like in the halls of circular or elliptic shape) because such walls concentrate the reflected sound (like spherical mirrors) in particular areas that leads to a non-uniform sound intensity in the audience area. This is well known but some architects push for beauty and originality at the expense of acoustics – an example is the new concerts hall of the Stuttgart Conservatory of Music, built around 2000, that has a beautiful round shape and a horrible acoustics.

• Avoid strictly parallel plain walls (like those in halls of a strictly rectangular shape) because (resonance) standing waves with a highly non-uniform sound intensity (<u>nodes</u> and <u>antinodes</u>) can be formed between such walls. This is somewhat less important for the audience part of the hall since the sound is coming there from the stage and it is reflected from the walls obliquely, preventing formation of standing waves. Also resonances in big halls are less important because of the <u>diffraction</u>. But the effect is very important for the stage, where standing waves (that is, resonances) between parallel stage walls can lead to the effect that musicians do not hear each other well. So the side walls of the stage should not be parallel.

Absorption and reflection coefficients

Reflection coefficient r is defined as the ratio of the intensity of the reflected wave I_r to the intensity of the incident wave I_i :

$$I_r = rI_i$$

Incident wave, I_i

Reflected wave, I_r
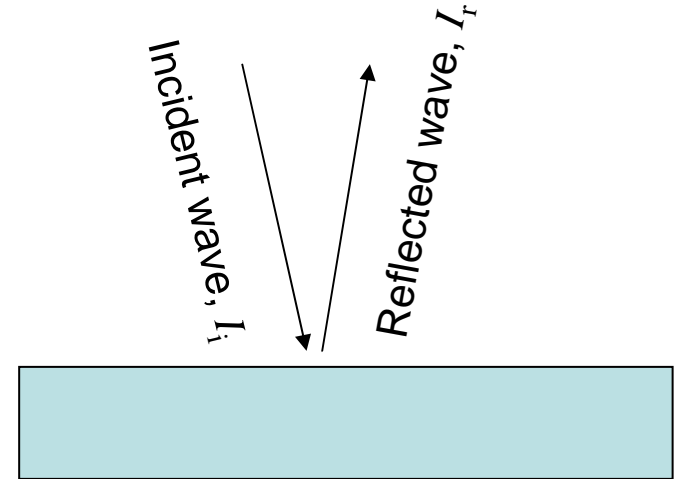
Since only a fraction of the sound (or light) is reflecting, the reflection coefficient satisfies

$$0 \leq r \leq 1$$

Everything that is not reflected is absorbed. The intensity of the absorbed sound I_a plus the one of the reflected sound I_r is exactly the intensity of the incident sound I_i

$$I_r + I_a = I_i$$

One can define the absorption coefficient a by

$$I_a = aI_i$$

The absorption and reflection coefficients satisfy

$$a + r = 1, \qquad 0 \leq a \leq 1, \qquad 0 \leq r \leq 1$$

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The sound propagating between two parallel walls in the direction perpendicular to the walls is forming standing waves because of the boundary conditions at the walls (node-node for the air displacement and antinode-antinode for the excessive pressure). The fundamental (maximal) wave length is $\lambda_1 = 2L$, the fundamental (minimal) frequency is $f_1 = v/\lambda_1 = v/(2L)$, and the whole overtone series is given by

$$f_n = nf_1 = \frac{v}{2L}n, \qquad n = 1,2,3,...$$

The situation in a room of a box shape with the sides L_x, L_y, L_z, is more complicated since there are, in general, three different fundamental frequencies and thus three different sets of harmonics. Moreover, there are standing waves that are directed obliquely to the walls. The complete expression for the resonance frequencies in the room has the form

$$f_{n_x,n_y,n_z} = \frac{v}{2}\sqrt{\left(\frac{n_x}{L_x}\right)^2 + \left(\frac{n_y}{L_y}\right)^2 + \left(\frac{n_z}{L_z}\right)^2}, \qquad n_x,n_y,n_z = 0,1,2,3,...$$

One can see that there are a lot of different resonances (standing waves) in the room! In this formula, at least one of the numbers n_x, n_y, n_z should be nonzero. One can sing very loud even with a small lousy voice in a bathroom, if one hits one of the resonance frequencies.

In concert halls, one should generally avoid resonances. Nonresonant sound does not form standing waves and its intensity is more or less uniform throughout the hall.

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Reverberation time (RT) shows how long the sound can be heard in the hall after the sound sourse stops to produce the sound. The definition of the reverberation time depends on what we define as the end of the sound we hear. Since our ears are very sensitive to quiet sounds, it was postulated that the sound ends when its intensity I becomes 10^{-6} of its initial intensity I_0. This corresponds to the decrease of the SIL by 60 dB.

Physically, reverberation is due to many echoes that reach our ears from different directions. In well-built halls, there are very many small echoes that merge into an echo continuum with smoothly decreasing intensity. In this case one speaks of a good texture. (Texture is defined as the echo intensity versus time). To the contrary, if there is one or several strong echoes separated by time intervals, the texture of the reflected sound consists of spikes and the sound becomes unpleasant.

RT depends on frequency f and it becomes longer at low frequencies because of smaller sound absorption.

Halls designed for slow music like singing (for instance churches) should have a long reverberation time, so that the echo supports the singers. To the contrary, theaters require a short reverberation time so that the echo does not make the speech indistinguishable. Instrumental music requires a trade-off in the reverberation time, so that different halls can be better suited for slow and fast music, like classical and romantic music (transparent Mozart requires a shorter RT while massive Brahms requires a longer RT).
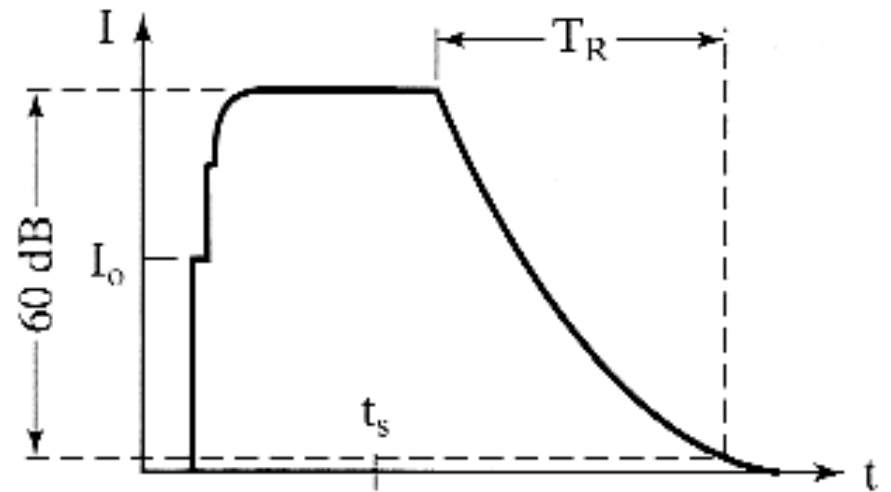
The semi-empirical formula for the RT reads

$$T_R = \frac{k}{v}\frac{V}{A}, \qquad A = a_1 A_1 + a_2 A_2 + ...$$

where k is a big numerical factor related to the attenuation of the sound by 10^{-6} in the definition of the RT, v is the speed of sound, V is the volume of the hall and A is the total absorption defined by the areas of all surfaces, A_1, A_2, etc., and their absorption coefficients, a_1, a_2, etc. RT thus scales with the linear size of the hall. Highly reflecting walls with small absorption coefficients can make RT very long that makes speech non-distinct. Choosing materials with different absorption coefficients (also depending on the frequency!), the architect can control the RT and finer details of the acoustics.
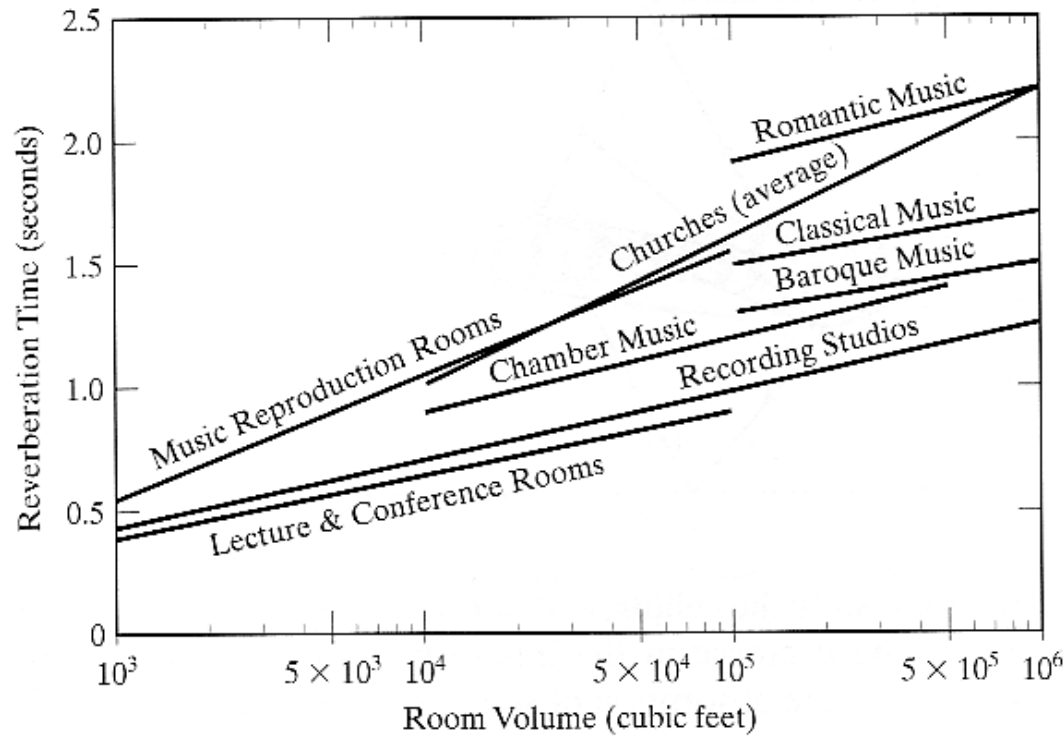
How the sound travels from the source (S) to the listener (L) in a room
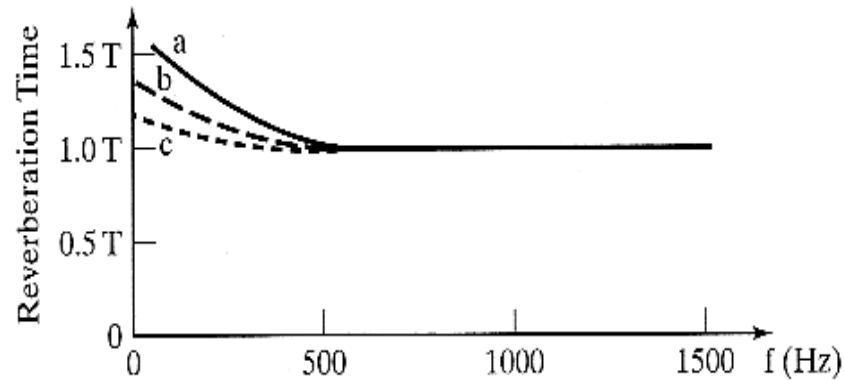

Direct Sound

Reflected sound

S

L

I

Direct sound

Reflected sound

t
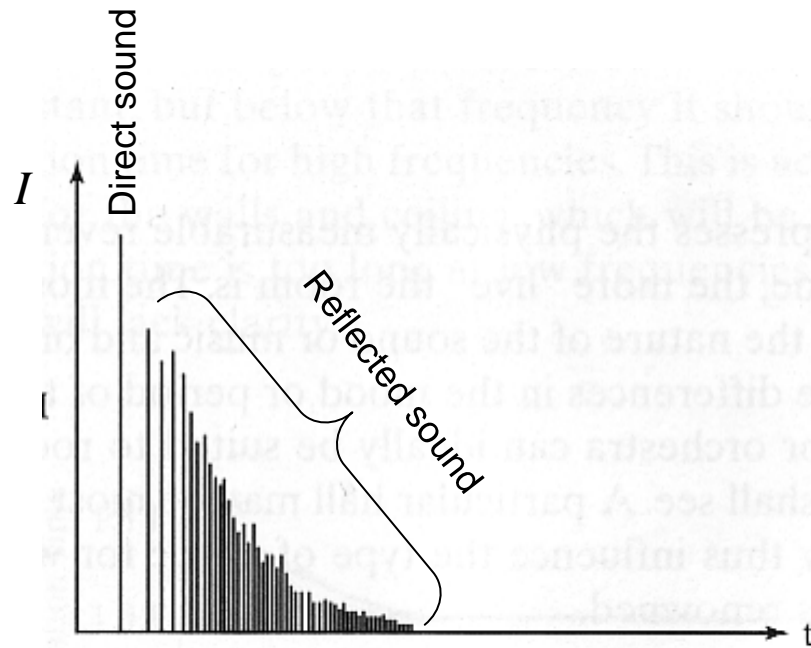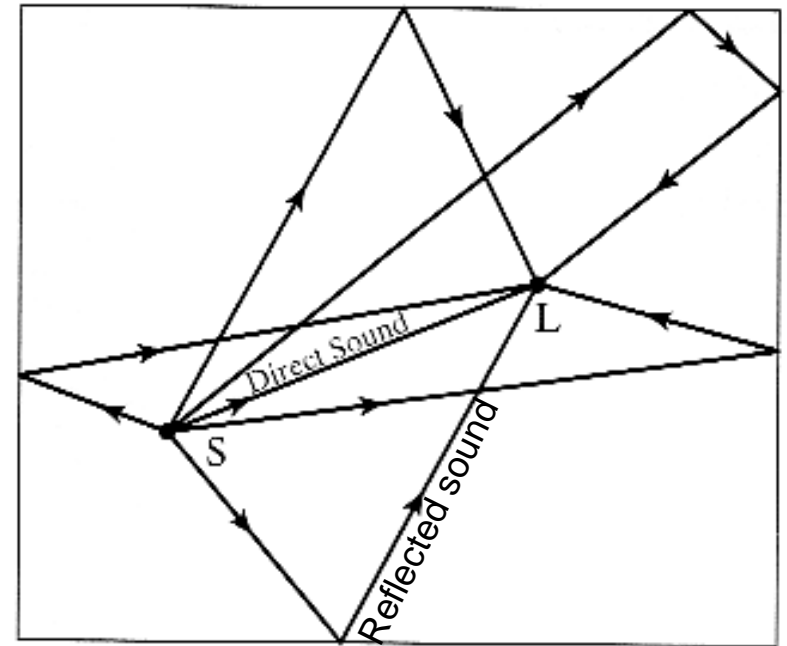
Echo in a room (good texture)

I

T_R

60 dB

I_o

t_s

t

Definition of the reverberation time

Typical reverberation times

Good texture:
Many small echoes

Bad texture:
A single strong echo present
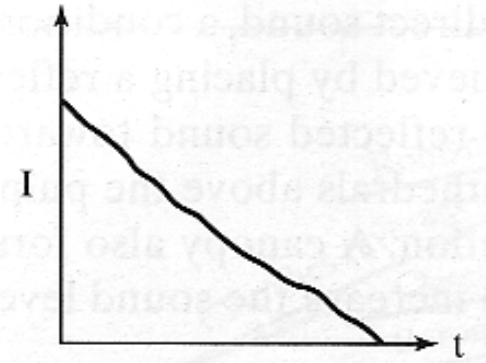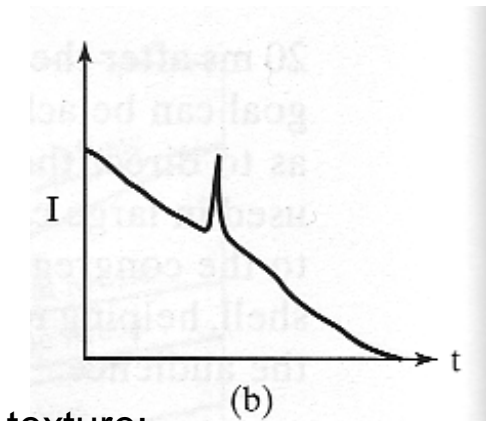
Frequency dependence of the reverberation time:
a) „Warm" acoustics; b) Normal acoustics; c) „Brilliant" acoustics

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• Fullness vs Clarity: These characteristics refer to the amount of the reflected sound relative to that of the direct sound. Fullness is achieved when there is a lot of reflected sound. Clarity is acieved when the direct sound is dominating

• Warmth vs Brilliance: Warmth is achieved if the RT at low frequency significantly exceeds that at high frequencies. If the RT does not increase so much at low frequencies, the acoustics is brilliant.

• Intimacy: If the time delay between the direct sound and the first reflected sound reaching the ears is short, as it is the case in small rooms, we have a feeling of intimacy. In large halls this delay becomes big and the feeling of intimacy gets lost. To correct it, a reflecting screen close to the source of sound can be used. Then the time delay becomes small and the feeling of intimacy gets restored. This is an example of how our feelings can be tricked.

• Texture: As said above, texture is the dynamic pattern of sound reflections. Good texture is a smoothly decreasing function of time due to many small echoes. Bad texture contains spikes from strong single echoes.