Reverberation

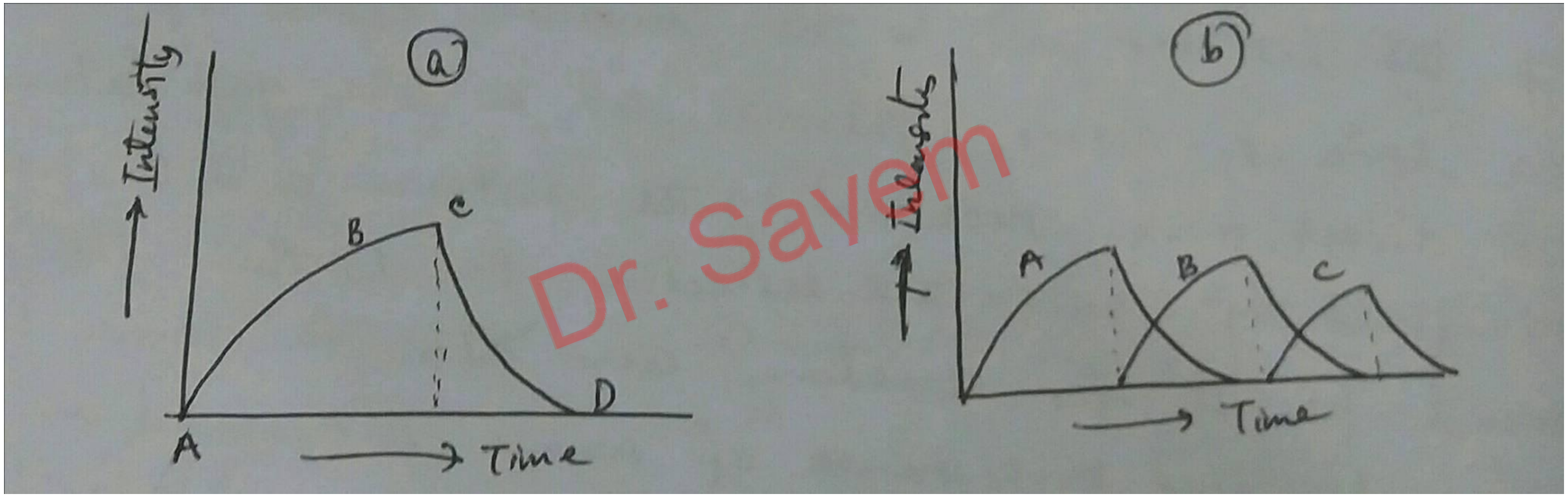
For a listener in a room or an auditorium the sound waves received from the direct waves and the reflected waves due to multiple reflections at the various surfaces-like walls, ceiling etc. The quality of the note received by the listener will be the combined effect of these two sets of waves. There is also a time gap between the direct wave received by the listener and the waves received by the successive reflection. Due to this, sound persists for sometime even after the source has stopped. This persistence of source is termed as reverberation. The time gap between the initial direct note and the reflected note upto the minimum audibility level is called reverberation time.

The reverberation time will depend on the size of the room or the auditorium, the nature of the reflecting material on the wall and the ceiling and the area of the reflecting surfaces.

In a good auditorium, it is necessary to keep the reverberation time neglecting small.

If the note is continuously sounded, the intensity of sound at the listener's ears gradually increases. After sometime a balance is reached between the energy emitted per second by the source and the energy lost or dissipated by the walls or other materials. The resultant energy attains an average steady value, and to the listener the intensity of sound appears to be steady and constant.

This is represented by the portion ABC of the curve ABCD. If the source stops emitting sound, the intensity of sound falls exponentially as shown by the curve CD. When the intensity of sound falls below the minimum audibility level, the listener will not hear the sound.



When a series of notes are produced in an auditorium (say speech or music) each note will give rise to its own intensity curve with respect time. The curves for these notes are shown in Fig (b).

For clear audibility:

For clear audibility of speech or music, it is necessary that

(1) Each separate note should give sufficient intensity of sound in every part of the auditorium.

(2) Each note should die down rapidly before the minimum average intensity due to the next note is heard by the listener. This is particularly important for speech. In the case of music comparatively more reverberation can be tolerated.

Sabine's Reverberation Formula

Sabine developed the reverberation formula to express the rise and falls of sound in a auditorium. The main assumptions are:

(1) The average energy per unit volume is uniform. It is represented as σ.

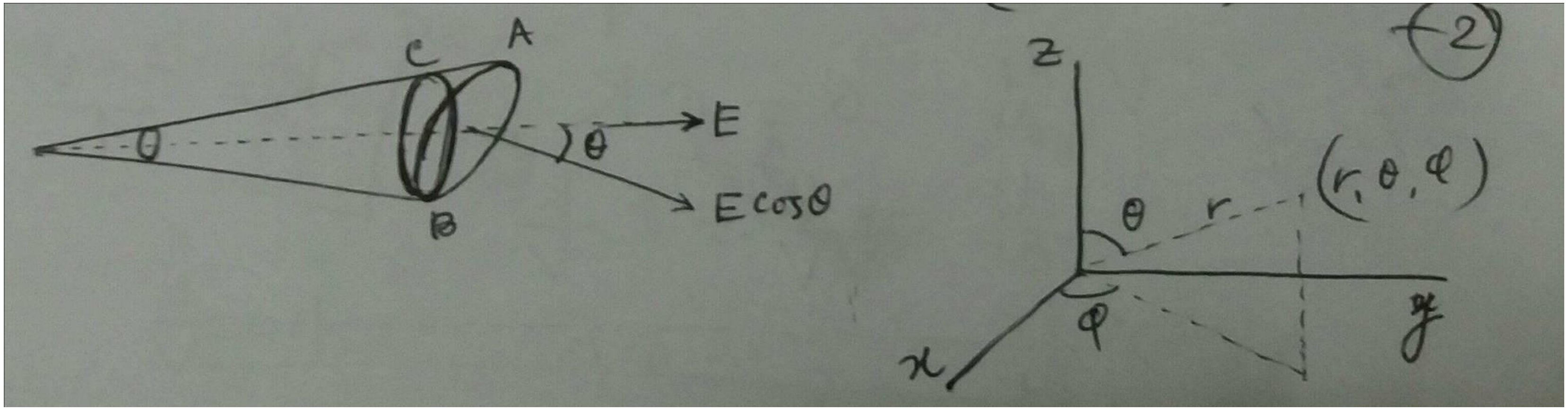
(1) The energy is not lost in the auditorium. The energy lost is only due to the absorption of the material of the walls and ceiling and also due to the escape through windows and ventilators. Both these factors are included in the term "absorption" of energy.

Suppose a source is producing sound continuously. This sound energy is propagated in all directions. The energy that is contained in a solid angle

$$d\Omega = \frac{\sigma d\varphi}{4\pi} \qquad (1)$$

Let this energy be incident on a unit surface area of the wall at an angle θ. If the velocity of sound is v, the total energy per second on a unit surface area of the wall:

$$= \frac{\sigma d\varphi}{4\pi}(\cos\theta)v \qquad (2)$$



The total energy falling per second within a hemisphere:

$$= \frac{\sigma v}{4\pi}\int_0^{\pi/2} 2\pi \sin\theta \cos\theta d\theta = \frac{\sigma v}{4} \qquad (3)$$

Suppose α is the absorption coefficient of the walls, that refers to the direction of the incident energy not reflected from walls. The amount of energy absorbed per second per unit area $= \dfrac{\alpha\sigma v}{4}$

If A is the area of the walls and the other absorbing materials including ceiling, windows and ventilators etc, the amount of energy absorbed per second $= \dfrac{A\alpha\sigma v}{4}$

Suppose, the source supplies energy at the rate of Q units per second,

the rate of increase of energy $= Q - \frac{A\alpha\sigma v}{4}$ (4)

On the other hand, let V be the volume of the auditorium, the rate of increase of energy $= \frac{d}{dt}(V\sigma) = V\frac{d\sigma}{dt}$ (5)

From equ (4) and (5)

$$V\frac{d\sigma}{dt} = Q - \frac{A\alpha\sigma v}{4}$$

$$\Rightarrow V\frac{d\sigma}{dt} = Q - \sigma K$$

$$\Rightarrow \frac{d\sigma}{dt} = \frac{Q}{V} - \sigma\frac{K}{V} \qquad (6)$$

The general solution of equ (6)

$$\sigma = B + be^{-\frac{K}{V}t} \qquad [B = \frac{Q}{K} = \frac{4Q}{A\alpha v}]$$

When t =0, σ =0. So, 0 = B+b or, b = -B

$$\sigma = B - Be^{-\frac{K}{V}t} = B(1 - e^{-\frac{K}{V}t})$$

$$\therefore \sigma = \frac{4Q}{A\alpha v}(1 - e^{-\frac{A\alpha v}{4V}t}) \qquad (7)$$

Equation (5) represents the rise of average sound energy per unit time from the time the source commences to produce sound. The maximum value of average energy per unit volume:

$$\sigma_{\max} = \frac{4Q}{A\alpha v} \qquad (8)$$

Similarly, after the source ceases to emit sound, the decay of the average energy per unit volume is given by:

$$\therefore \sigma = \frac{4Q}{A\alpha v} e^{-\frac{A\alpha v}{4V}t} = \sigma_{\max} e^{-\frac{A\alpha v}{4V}t} \qquad (9)$$

The factor $\frac{A\alpha v}{4V}$ gives the reverberation time in the auditorium. If σ_0 is the minimum audible intensity after time t_1, then from equ (9)

$$\sigma_0 = \sigma_{\max} e^{-\frac{A\alpha v}{4V}t_1} \qquad (10)$$

$$\Rightarrow \sigma_{\max} = \sigma_0 e^{\frac{A\alpha v}{4V}t_1}$$

$$\Rightarrow \log\left(\frac{\sigma_{\max}}{\sigma_0}\right) = \frac{A\alpha v}{4V} t_1$$

For calculating the reverberation time, a standard steady intensity is required. Sabine took the value of

$$\frac{\sigma_{\max}}{\sigma_0} = 10^6$$

$$\therefore \log(10^6) = \frac{A\alpha v}{4V} t_1$$

Velocity of sound v= 350 m/s

$$\Rightarrow t_1 = \frac{0.158V}{A\alpha} \qquad (11)$$

Equ(11) is the expression of reverberation time.

Problem: The volume of a room is 600 m^3. The area of wall, floor and ceiling are 200, 120 and 120 cm^3 respectively. The average absorption coefficient for walls, ceiling and floor are 0.03, 0.80 and 0.06. Calculate the average sound absorption coefficient and the reverberation time.

Sol: The average sound absorption coefficient is:

$$\alpha = \frac{\sum \alpha A}{\sum A} = \frac{\alpha_1 A_1 + \alpha_2 A_2 + \alpha_3 A_3}{A_1 + A_2 + A_3}$$

$$= \frac{0.3 \times 220 + 0.8 \times 120 + 0.06 \times 120}{220 + 120 + 120} = 0.24$$

Reverberation time:

$$t_1 = \frac{0.158 V}{\alpha \sum A} = \frac{0.158 \times 600}{0.24 \times 460} = 0.86 \text{ s}$$