Sound waves are classified into three categories on the basis of frequency.

1. Infrasonics (below 20 Hz)
2. Audible sound (between 20 Hz to 20.000 Hz)
3. Ultra sound (above 20,000 Hz)

Audible sound is further classified as

a) **Musical sound** which produces pleasing effect on the ear.
b) **Noises** which produces unpleasant effect on the ear.

Characteristics of musical sound

a) Pitch – Pitch is the characteristic of sound that distinguishes between a shrill sound and a grave sound.
b) Quality – The quality of sound is that characteristic which enables us to distinguish between two notes of the same pitch and loudness produced by two different voices.
c) Intensity of sound – It is the energy of sound wave crossing per unit time through unit area at right angles to the direction of propagation.
d) Loudness – It is the degree of sensation produced in the ear.

Weber-Fechner law

Loudness of sound is defined as the degree of sensation produced on the ear. This cannot be measured directly. So that it is measured in terms of intensity. Loudness is proportional to logarithmic value of intensity.

$$L \propto \log I; \quad L = k \log I$$

Sound Intensity Level

It is the ratio of intensity of a sound (I) to the standard intensity of sound (I_o) .

$$\beta = \log_{10} (I/I_o)$$

Bel – 1 bel is defined as the relative intensity between two sound notes if one is 10 times more intense than the other.

Decibel – It is the smallest unit compared to Bel. It is the standard unit used to measure the loudness. One decibel is equal to one tenth of bel. An increase of sound intensity level by 1 dB would increase the intensity by 26 %.

Absorption coefficient

The absorption coefficient of a material is defined as the ratio of the sound energy absorbed by the surface to that of the total sound energy incident on the surface.

$$a = \frac{\text{Sound energy absorbed by the surface}}{\text{Total sound energy incident on the surface}}$$

The absorption coefficient can also be defined as the rate of sound energy absorbed by a certain area of surface to that of an open window of same area.

$$a = \frac{\text{Sound energy absorbed by } 1\text{m}^2 \text{ of surface}}{\text{Sound energy absorbed by } 1\text{m}^2 \text{ of open window}}$$

Reverberation time

The persistence of audible sound, even after the source has stopped to emit the sound is called reverberation. The time during which the sound persists in the hall is called as reverberation time.

Reverberation time is also defined as the time taken by the sound to fall to one millionth of its original intensity, after the source of sound is stopped.

$$I = \frac{I_0}{10^6}$$

When the reverberation time is lower than the critical value, sound becomes inaudible by the observer and the sound is said to be dead and if the reverberation time is too large, echoes are produced. Therefore, the reverberation time should have some optimum value.

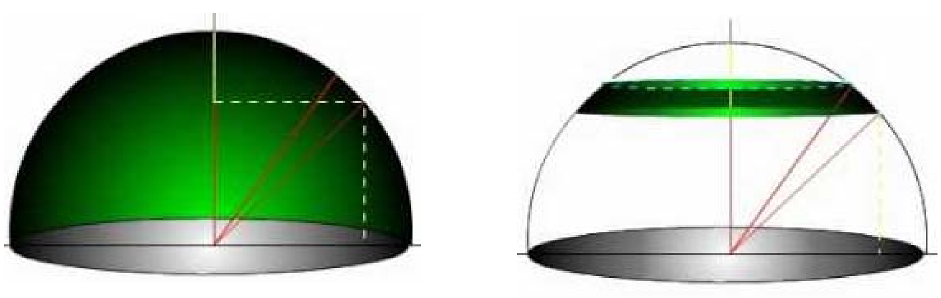
Sabine's law

If V is the volume of the hall, a is the average absorption coefficient and S is the total surface area, the reverberation time can be related as

$$T = \frac{0.167\,V}{\sum aS}$$

Derivation of Sabine's law

Let us consider small element *ds* on a plane wall AB as shown in fig.



Assume that this element *ds* receives sound energy. Taking O as a mid-point on ds, two semicircles are drawn with radii r and r+dr. Consider a small shaded portion between the circles lying between two radii drawn at angles θ and θ+dθ.

Radial length of the shaded portion = dr

Arc length of the shaded portion = r dθ

Area of the shaded portion = r dθ dr

Imagine the whole figure is rotated about the normal through an angle dϕ and shaded portion travels through a small distance dx and thus traces a elemental volume dV.

Distance travelled by this shaded portion, dx = r sin θ dϕ

Volume traced by the shaded portion, dV = r dθ dr .r sin θ dϕ

If E is the sound energy density, then sound energy present within the volume element dV,

$$= E \,.\, dV$$
$$= E.\, r^2 \sin\theta \, d\theta \, dr \, d\phi$$

This sound energy is travelling equally in all directions in total solid angle of 4π. Sound energy travels from the volume dV per unit solid angle

$$= (E.dV)/4\pi$$

Solid angle subtended by the area ds at this element of volume dV,

$$= ds.\cos\theta/r^2$$

Sound energy from the elemental of volume dV travelling towards ds is given by

$$= E.ds.\sin\theta.d\theta\ dr\ d\phi\ /4\pi$$

The total sound energy falling on ds per second = E.v.ds/4, where v is the velocity of sound.

If a is the absorption coefficient of the wall AB of which ds is a part, then the sound energy absorbed by ds in one second = E.v.ds.a/4

Total energy absorbed per second by the whole enclosure = $E.v.\Sigma ads/4$

$$= EvA/4$$

Where $A = \Sigma$ a.ds is total absorption of sound in all the surfaces on which sound energy is incident.

Growth of sound decay

If P is the sound power output and V is the total volume of the hall, then total sound energy in the hall at a given instant 't' = EV.

Therefore, rate of growth per second = V.dE/dt

Rate of emission of sound energy = Rate of growth of sound energy in room + Rate of absorption of sound by the walls.

i.e. P = V.dE/dt + EvA/4 ……………. (1)

When steady state if reached, dE/dt = 0, and if steady state energy density is denoted as E_m,

$P = E_m vA/4$

Therefore, $E_m = 4P/vA$

Dividing equation (1) by V, we get

$(dE/dt) + (EvA/4V) = P/V$

Putting $vA/4V = \alpha$, $(dE/dt) + E\alpha = 4P/vA$

Multiplying with $e^{\alpha t}$ on both sides,

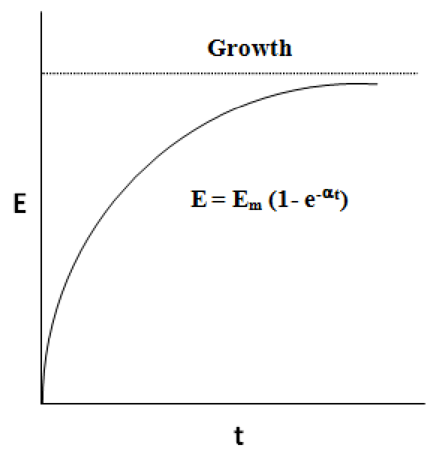
$(dE/dt + E\alpha)\ e^{\alpha t} = 4P\alpha e^{\alpha t}/vA$

$d/dt(Ee^{\alpha t}) = 4P\alpha e^{\alpha t}/vA$

Integrating on both sides,

$Ee^{\alpha t} = (4Pe^{\alpha t}/vA) + K$ …………......... (2)

where K is a constant of integration. The value of K is determined by considering the boundary conditions.



Sound energy grows from the instant the source begin to emit sound at t = 0 and E = 0

Applying this in equation (2), we get

$K = -4P/vA$

Therefore,

$Ee^{\alpha t} = (4Pe^{\alpha t}/vA) – (4P/vA)$

$E = (4P/vA) – (4Pe^{-\alpha t}/vA)$

$E = 4P/vA\ (1- e^{-\alpha t})$

Therefore, $\mathbf{E = E_m\ (1- e^{-\alpha t})}$

This equation expresses the growth of sound energy density 'E' with time 't'. This indicated that E increases with t, and when $t \to \infty$, $E = E_m$.

Decay of sound energy

Assume that, when sound energy has reached its steady (maximum value) state Em, sound energy is cut off. Then the rate of emission of sound energy, P = 0.

Therefore, equation (2) can be written as $Ee^{\alpha t} = K$

Substituting the boundary conditions $E = E_m$ at t = 0 and P = 0, we get

$E_m e^0 = 0 + K$

$K = E_m$

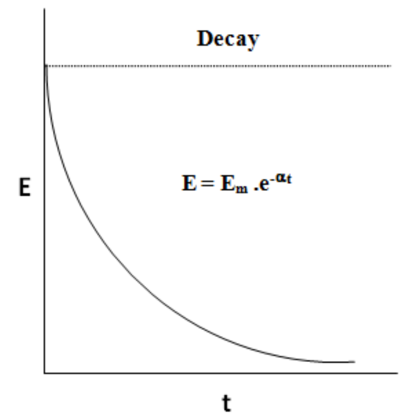
Therefore, we get

$Ee^{\alpha t} = E_m$

$E = E_m/e^{\alpha t}$

Therefore, $\mathbf{E = E_m. e^{-\alpha t}}$

This equation represents the decay of sound energy density with time after the source is cut off.



Expression for reverberation time

The standard reverberation time is the time taken by the sound to fall of its intensity to one-millionth of its initial value after the source is cut off. Now, the value of sound energy density before cut off is E_m, at standard reverberation time, it reduces to

$$E = E_m/10^6$$

To calculate T, we put $E = E_m.10^{-6}$ and t = T,

$E_m.10^{-6} = E_m.\ e^{-\alpha T}$

$e^{-\alpha T} = 10^{-6}$

$e^{\alpha T} = 10^6$

Taking log on both sides, we have

$\alpha T = 6\log_e 10$

$T = (6x2.3026x1)/\alpha$

$T = (6x2.3026x1) / (vA/4V)$

By using velocity of sound, v = 340 m/s

T = 0.165 V / A

or

T = 0.165 V / Σas

This equation is in agreement with the experimental values obtained by Sabine.

<u>Factors affecting acoustics of buildings and their remedies</u>

The factors affecting acoustics of buildings and their remedies are as follows:

1. **Reverberation time:** If the reverberation time is very small, the sound intensity decreases very fast and makes the sound appear dead. On the other hand, a large reverberation time caises mixing of different syllables and hence causes confusion.

   For good quality sound, optimum reverberation time is required.

   Remedies:

i) Heavy curtains with folds are used to reduce reverberation time by increasing absorption of sound
ii) Floor is covered with carpets to absorb sound.
iii) Windows and openings are provided in the hall which can be opened or closed to control the reverberation time.
iv) Walls and ceilings are covered with sound absorbing materials.
v) If the hall is filled to its maximum capacity of audience, reverberation time is less.

2. **Loudness:** There should be adequate loudness in all parts of the hall.
   Remedies:
   i) Large sounding boards are used behind the speaker facing the audience.
   ii) Loudspeakers are used to increase the loudness.
   iii) Low ceilings help to reflect the sound towards the audience.
   iv) Sound absorbing materials are used in those parts of the hall where sound intensity is large.

3. **Echo:** The reflection of sound from a distant reflecting surface is known as echo. If the echo reaches the listener about $1/17^{th}$ of a second after the direct sound, the listener hears two sounds instead of one which causes confusion. Such echoes mush be eliminated in halls.
   Remedy: High ceilings and distant walls are covered with second absorbing materials.

4. **Echelon effect:** Succession of echoes produced by a set of regularly spaced reflecting surfaces like staircase causes confusion in original sound. This effect is known as echelon effect.
   Remedy: The regularly spaced reflecting surfaces like stairs are covered with sound absorbing materials like carpets.

5. **Focusing:** Concave and parabolic surfaces in the hall focus sound. This causes concentration of sound in certain regions of the hall which is not desirable.
   Remedies: Curved surfaces are avoided, If there are curved surfaces, they are covered with sound absorbing materials.

6. **Resonance:** Loose fitting window panels and some other objects resonate at some audible frequencies creating more sound of these frequencies. This distorts the original sound.
   Remedies: Window panels are fixed properly, Vibrating objects are placed on sound absorbing materials.

7. **Noise:** Noise from different sources adversely affects the quality of sound in a hall. The noise can be air borne, structure borne or inside noise.
   a) ***Air borne noise:*** the external noise, for example of traffic, which enters the halls through doors, windows and ventilators is known as external noise.
      Remedies:
      i) Openings for ventilators inside the hall are avoided.
      ii) Doors and windows are provided with rubber covering on frames so that they shut without any gaps.

iii) Double doors and windows having separate frames enclosing sound absorbing materials are used.

b) ***Structure borne noise:*** Noise produced by activities like drilling and hammering or the vibrations of heavy machinery is transmitted through the structure of the building. This is known as structure borne noise.

Remedies:

i) Heavy machinery is mounted on sound absorbing materials like wood or rubber.

ii) Double walls are used with space between them.

c) ***Inside noise:*** It is the noise produced inside the hall by machinery, fans, air conditioners etc.

Remedies:

i) Sound absorbing materials and curtains are provided near the sources of noise.

ii) The sources of noise are mounted on sound absorbing materials.