UNIT- VIII

14. ACOUSTICS OF BUILDINGS & ACOUSTIC QUIETING

REVERBERATION AND REVERBERATION TIME

A room with hard walls no furniture and no drapes , echoes. To hear well in a room or auditorium it may seem that the walls should not absorb and sound .This would lead to echoing .A room especially a large room with an excess of sound absorbing materials such as large soft drapes and soft stuffed furniture may have a quality referred to as dead. Too much absorption results in too low an intensity. Both these types of rooms are called poor acoustics. A balance must be there fore obtained.

When the sound is switched on intensity slowly builds up when it is switched off the intensity drops slowly . The prolongation of sound inside a room or hall even after the source producing the sound is turned off is called reverberation this is due to multiple reflections from the walls ceiling floor and other reflecting materials present in the hall.

The reverberation time for a room is the time required for the intensity to drop to one millionth (10^{-6}) of its initial value.

Reverberation time can be expressed interms of sound levels (in dB) rather than intensity . If the initial intensity is I_i and the final intensity I_f is 10^{-6} I_i then

$$dB_i = 10 \log I_i / I \text{ (standard)}$$
$$dB_f = 10 \log I_f / I \text{ (standard)}$$
$$dB_i - dB_f = 10 \log (I_i / I_f)$$
since $I_i / I_f = 10^6$
$$dB_i - dB_f = 10 \log 10^6$$
$$= 6*10 = 60$$

The reverberation time is the time required for the intensity to drop by 60 decibels . I t depends on the volume V of the room.It also depends on the absorption of all parts of the room of the room walls furniture people and so forth . Some parts may be highly absorbent and some absorb only little.

BASIC REQUIREMENTS OF ACOUSTICALLY GOOD HALL

The reverberation of sound in an auditorium is mainly due to multiple reflections at various surfaces inside. The volume and the shape of the auditorium and the sound absorption inside influence the behaviour of sound. By varying the absorption of sound inside the hall the reverberation time can be brought to optimum value. The following are the basic requirements of acoustically good hall.

1) The volume of the auditorium is decided by the type of programme to be conducted there and also the number of seats to be accommodated. A musical hall requires a large volume whereas a lecture hall requires a smaller volume. In deciding the volume of the hall its height plays an important role than its length and breadth. The ratio between the ceiling

height and breadth should in deciding the volume of the hall the following guidelines may be followed.

i) In cinema theatres – 3.74 to4.2 m^3 per seat
ii) In lecture halls – 2.8 to 3.7 m^3 per seat
iii) In musical halls – 4.2 to 5.6 m^3 per seat

2) The shape of the wall and ceiling should be so as to provide uniform distribution of sound throughout the hall. The design of a hall requires smooth decay and growth of sound . To ensure these factors the hall should have scattering objects walls should have irregular surface and walls must be fixed with absorptive materials . In fig 5.1 a design which enables uniform distribution of sound is presented.

3) The reverberation should be optimum i.. e. neither too large nor too small . The reverberation time should be 1 to 2 seconds for music and 0.5 to 1 second for speech to control the reverberation the sound absorbing materials are to be chosen carefully.

4) The sound heard must be sufficiently loud in every part of the hall and no echoes should be present.

5) The total quality of the speech and music must be unchanged i.e. the relative intensities of the several components of a complex sound must be maintained .

6) For the sake of clarity the successive syllables spoken must be clear and distinct i.e. there must be no confusion due to overlapping of syllables.

7) There should be no concentration of sound in any part of the hall.

8) The boundaries should be sufficiently sound proof to exclude extraneous noise.

9) The should be no Echelon effect.

10) There should be no resonance within the building .

11) The hall must be full of audience.

ABSORPTION COEFFICIENT

Since different materials absorb sound energy differently absorption of all the materials are expressed in terms of absorption coefficient.

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

$$\text{i.e. Abdortion coefficient } a = \frac{\text{Sound energy absorbed by the surface}}{\text{Total sound energy incident on the surface}}$$

As all sound waves falling on an open window a pass through an open window is taken to be a ;perfect absorber of sound and absorption coefficient of all substance are measured in terms of open window unit(O. W. U) Absorption coefficient of a surface is also defined as the reciprocal of its area which absorbs the same sound energy as absorbed by unit area of an

open window. The absorption coefficient of a given material depends on the frequency of the sound also . It is generally higher at higher frequencies.

Sound absorption coefficient of some materials (at 500 H_z frequency range)

Meterial	Absorption coefficient O.W.U
Marble	0.01
Concrete	0.17
Cork	0.23
Asbestos	0.26
Carpet	0.30
Fibre board	0.50
Heavy curtains	0.50
Fibre glass	0.75
Perforated cellulose fibre tiles	0.80
Human body	0.50
Open window	1.0

SABINE'S FORMULA FOR REVERBERATION TIME

Now we are going to derive an expression for reverberation time inside a room of volume V. Sound is produced by a source inside the room. There sound waves spread and fall on the walls they are partly absorbed and pertly reflected . The sound energy inside the room at any instant is given by

Rate of growth of energy in the space Inside the room = rate of supply of energy by the source – rate of absorption by all the surface

After getting an expression for the above if we switch off the source supplying energy then due to absorption of energy by all the surfaces energy inside the room will decay and from the decay rate reverberation time can be calculated. This derivation is based on the assumption that there is a uniform distribution of sound energy inside the room.

1) Rate of supply of energy by the source

Rate of supply of energy by the source is nothing but the power of the source P.

2) Rate of absorption of sound inside the room

In order to calculate the absorption by the wall we consider a small element ds on a plane wall AB as shown in fig 5.2 this element receives sound energy from the volume infront of it Energy received by this element per second can be calculated by constructing a hemisphere around this element with radius 'υ' where υ is the velocity of sound . Energy from every volume element with in this hemisphere will reach the element ds per elements ds . From the same centre with radii γ and $\gamma+d\gamma$ two circles are drawn in the plane containing the normal. At angles θ and $\theta+d\theta$ with respect to the normal two radii are and the area (shaded in the figure) enclosed by these two radii between the circle is considered.

The are length of this area $=rd\theta$
Radial length $=dr$

Hence surface area of this element $=rd\theta dr$

This surface element is rotated about the normal through an angle $d\Phi$ and the circumferential distance moved by this elements is $r \sin\theta d\Phi$.

Volume traced out by this area element = area of the element * distance moved

$$dV = rd\theta dr(r \sin\theta \, d\Phi)$$
$$= r^2 \sin\theta d\theta dr d\Phi$$

If E is the sound energy density i.e. energy per unit volume then energy present in the is volume $=EdV$. Since the sound energy from this volume element propagates in all directions (i.e. through solid angle 4π)

$$\text{The energy traveling per unit solid angle} = \frac{EdV}{4\pi}$$

The energy traveling towards surface element ds alone falls on ds.
The energy traveling towards ds =energy traveling per unit solid anle *solid angle Subtended by ds at the volume element dV

$$\text{The solid angle subtended by area ds at this elements of volume dV} = \frac{ds\cos\theta}{r^2}$$

$$\text{Hence energy traveled towards ds from the Volume element dV} = \frac{EdV}{4\pi} \cdot \frac{ds\cos\theta}{r^2}$$

$$= \frac{E.r^2 \sin\theta d\theta dr d\Phi}{4\pi} \cdot \frac{ds\cos\theta}{r^2}$$

$$= \frac{Eds}{4\pi} \sin\theta \cos\theta \, d\theta d\Phi dr$$

Total energy received by ds in one second from the whole

$$\text{Volume in its front} = \frac{Eds}{4\pi} \int \sin\theta \cos\theta d\theta d\Phi dr$$

This equation has three variable sincewe consider the energy received per second r varies between 0 and v where is the velocity of sound θ varies between 0 and $\pi / 2$, Φ varies between 0 and 2π.

Hence energy received by ds per second

$$= \frac{Eds}{4\pi} \int_0^{\pi/2} \sin\theta\cos\theta d\theta \int_0^{\pi/2} d\Phi \int_0^{v} dr$$

$$= \frac{Eds}{4\pi} v*2\pi* \int_0^{\pi/2} \sin\theta\cos\theta d\theta$$

$$= \frac{Evds}{4} \int_0^{\pi/2} 2\sin\theta\cos\theta d\theta$$

$$= \frac{Evds}{4} (since \int_0^{\pi/2} 2\sin\theta\cos\theta d\theta = 1)$$

If a is the absorption of coefficient of the material of the wall ABthen energy absorbed by the surface element ds per second $= \frac{Evds}{4}a$

Hence total rate of absorption by all the surfaces of the wall

$$= \frac{Ev}{4}\Sigma ads$$

$$= \frac{EvA}{4}$$

Where Σads = A the total absorption a on all the surface on which sound falls.

3) The growth and decay of sound energy in the room

Let p be the power output i.e. rate of emission of energy from the surface and V the total volume of the room . Then the total energy in the room at the instant when energy density is E will be EV

Rate of growth of energy $= \frac{d}{Dt}(EV) = V\frac{dE}{dt}$

But at any instant rate of growth of energy in space= rate of supply of energy from the furface – rate of absorption by all the surfaces.

$$V\frac{dE}{} = p - \frac{EvA}{}$$

$$\frac{dt}{} \qquad \frac{}{4}$$

When steady state is attained dE/dt =0 and if the steady state energy density is denoted by E_m then its value is given by

$$0 = p - \frac{E_m vA}{4}$$

$$E_m = \frac{4p}{vA}$$

from equation

$$\frac{dE}{Dt} = \frac{p}{v} - \frac{vA}{4v}.E$$

$$\left(\text{Let } \frac{vA}{4v} = \alpha \text{ and hence } \frac{1}{v} = \frac{4\alpha}{vA} \right)$$

$$\frac{dE}{dt} = \frac{4p\alpha}{vA} - \alpha E$$

or

$$\frac{dE}{dt} + \alpha E = \frac{4p}{vA}.\alpha$$

multiplying both sides by $e^{\alpha t}$ we have

$$\left(\frac{dE}{Dt} + \alpha E \right) e^{\alpha t} = \frac{4p}{vA} \alpha e^{\alpha t})$$

Or

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

integrating the above equation we get

$$Ee^{\alpha t} = \frac{4p}{vA} e^{\alpha t} + k$$

where k is a constant of integration . Using the boundary conditions we can find the value of K

i) Growth of the energy density:- If t is measured from the instant the source start emitting sound . then initial condition is that at t=0 E=0, Applying this condition to equation we get

$$K = \frac{-4p}{vA}$$

substituting this value in equation we get

$$E\,e^{\alpha t} = \frac{4p}{vA}e^{\alpha t} - \frac{4p}{vA} \text{ or } E = \frac{4p}{vA} - \frac{4p}{vA}e^{-\alpha t}$$

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

or

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

The equation shows the growth of energy with time t. The growth is along the exponential curve shown in fig 5.3 which shows that E increases along the curve with time At t= 0,E = 0 and at

ii) Decay of energy density:- Let the source be cut off when E has reached the maximum value E_m . Now at t=0, p=0, E= E_m from equation K =E_m

substituting this value of K in equation

$E\,e^{\alpha t}$ E_m (since p=0)

Equation show s the decay of the energy density with time after the source is cut off. This decay is shown by the exponential curve .

4) Deduction of standard reverberation time (T) i.e. sabine's formula : We know that the persistence of audible sound in the room even after the source has stopped producing the sound is called reverberation and the standard time of rev3ereration T is defined as the time taken for the sound energy density inside a room to fall to one millionth of its initial maximum value hence to calculate T we put E_m /E =10^6 and t= T in equation

$$\frac{E}{E_m} = e^{\alpha T}\ 10^{-6} \text{ (or) } e^{\alpha T} = 10^6$$

Taking log hw have

$\alpha T = 6 \log_e 10 = 2.3026*6$

substituting forα

$$T = \frac{4*2.3026*6}{330} \cdot \frac{V}{A} \quad (v=330 m/s)$$

Or

$$T = \frac{0.165V}{A} = \frac{0.165V}{\Sigma aS}$$

This equation is in good agreement with the experimental values obtained by sabine .this is sabine's formula for reverberation time .

i) Directly proportional to the volume of the auditorium
ii) Inversely proportional to the areas of sound absorbing surfaces such as ceiling wall floor and other materials present inside the hall and
iii) Inversely proportional to the total absorption

It has been experimentally found that the reverberation time of 1.03 second is most suitable for all room having approximately a volume less that 350 meters.

METHOD 1

The first method is based on the determination of standard time of reverberation in the room without and with the sample of the material inside the room , If T_1 is the reverberation time without the sample inside the room then applying sabine's formula

$$\frac{1}{T_1} = \frac{A}{0.165V} = \frac{\Sigma aS}{0.165V}$$

Now with the sample inside the room reveration time T_2 is measured.

$$\frac{1}{T_2} = \frac{\Sigma aS + a_1 s_1}{0.165V}$$

Where a_1 is the absorption coefficient of the area S_1. From the above equation we have

$$\frac{a_1 S_1}{0.165V} = \left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

OR

$$a_2 = \frac{0.165\,V}{S_1}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

Hence knowing the terms on the right hand side of this equation the absorption coefficient a_1 of the given material can be calculated .

FACTORS AFFECCTING THE ARCHITECTURAL ACOUSTICS AND THEIR REMEDIES

By an acoustically good hall we mean that every syllable or musical note reches an audible level of loudness at every point of the hall and then quickly dies away to make Room for for the next syllable or group of note. The deviation from this makes the hall defective acoustically . Following factors affect the architectural acoustics.

1) In a hall when reverberation is large there is overlapping of successive sound which results in loss of clarity in hearing.On the other hand if the reverberation is very small the loudness is inadequate .Thus the time of reverberation for a hall should neither be too large nor too small . It must have a definite value which may be satisfactory both to the speaker as well as to the audience . The preferred value of the time or reverberation is called the optimum reverberation time . A formula for standard time of reverberation was given by W. C sabine which is

$$T = \frac{0.165V}{A} = \frac{0.165V}{\Sigma aS}$$

Where A is the total absorption of the hall V its volume in cubic metre and S is the surface area in square metre.

Experimentally its is observed that the time of reverberation depends upon the size of the hall loudness of sound and on the kind of the music fro which the hall is used . For a frequency of 512 H_z the best time of reverberation lies between 1 and 1.5 sec for small halls and up to 2-3 seconds for larger ones.

REMEDY:- The reverberation can be controlled by the following factors

1) By providing windows and ventilators which can be opened and closed to make the value of the4 time of reverberation optimum
2) Decorating the walls by pictures and maps
3) Using heavy curtains with folds
4) By lining the walls with absorbent materials such as felt celotex fibre board glass wool etc
5) Having full capacity of audience (please remember that empty hall reverberarate each person is equivalent to about 0.50 sq metre area of an open window)
6) By covering the floor with carpets
7) By providing acoustic tiles.

LOUDNESS:- With large absorption the time of reverberation will be smaller. This will minimise the chances of confusion between the different syllables by the intensity of sound may go ;below the level of intelligibility of hearing . Sufficient loudness at every point in the hall is an important factor for satisfactory hearing .

REMEDY:- The loudness may be increased by

1) Using large sounding boards behind the speaker and facing the audience large polished wooden reflecting surfaces immedialtely above the speaker are also helpful
2) Low ceiling are also of great help in reflecting the sound energy towards the audience.
3) By providing additional sound energy with the help of equipments like loud speakers. To achieve uniform distribution of intensity through out the hall loudspeakers are to be positioned carefully .

FOCUSSING:-If there are focusing surface such as concave spherical cylindrical or parabolic ones on the walls or ceiling of the hall they produce concentration of sound in particular regions while in come other parts no sound reaches at all. In this way there will be regions of silence or poor audibility . If there are extensive reflecting surfaces in the hall the reflected and direct sound waves may form stationary wave system thus making the sound intensity distribution bad and uneven.

REMEDY:- For uniform distribution of sound energy in the hall

1) There should be no curved surfaces . If such surfaces are present they should be covered with absorbent material
2) Ceiling should be low .
3) A paraboloidal reflected surface arranged with the speaker at the focus is also helpful in sending a uniform reflected beam of sound in the hall.

ECHOES:- An echo is heard when direct sound waves coming from the source and its reflected wave reach the listener with a time interval of about 1/7 second/ The reflected sound arriving earlier than this helps in raising the loudness whole those arriving later produce echoes and cause confusion

REMEDY :- Echoes may be avoided by covering the long distant walls and high ceiling with absorbent material

ECHELON EFFECT:- A set of railing s or any regular spacing of reflecting surfaces may produce a musical note due to the regular succession of echoes of the original sound to the listerner. This makes the original sound confusing or unintelligible .

REMEDY:- So this type of surface should be avoided or covered with proper sound absorbing materials.

RESONANCE:- Sometimes the window panes sections of the wooden portions and walls lacking in rigidity ate thrown into forced vibrations and create sound. For some note of audio frequency the frequencies of forced vibrations any be the same thus resulting in the resonance . Moreover if the frequency of the of the created sound is not equal to the original sound at least certain tone s of the original music will be reinforced. Due to the interference between original sound and created sound the original sound is distorted . Thus the intensity of the note is entirely different from the original one enclosed air in the hall also causes resonance.

REMEDY:- Such resonant vibrations should be suitably damped.

NOISE:- Generally there are three types of noises which are very troublesome they are

1) Air- borne noise
2) Structure borne noise and
3) Inside noise

The prevention of the transmission of noise inside or outside the hall is known as sound insulation . This is also known as sound proofing . The method of sound insulation depends on the type of noise to be treated . Here we shall discuss the different types of noises and their sound insulation.

AIR BORNE NOISE:- The noise which commonly reaches the hall from outside through open window doors and ventilators is known as air born noise since this noise is transmitted through the air it is called so.

REMEDY :- Sound insulation for the reduction of air borne noise can be achieved by the following methods

1) By allotting proper places for doors and windows
2) By making arrangements for perfectly shutting doors and windows
3) Using heavy glass in doors windows and ventilators
4) Using double doors and window with separate frames and having insulating material between them
5) By providing double wall construction floating floor construction suspended ceiling construction box type construction etc.
6) By avoiding opening s for pipes and ventilators

STRUCTURE BORNE NOISE:- The noise which are conveyed through the structures of the building are known as structural noise. The noises may be caused due to structure . The most common sources of this type of sound are foot steps street traffic operating machinery moving of furniture etc

REMEDY:- Sound insulation for the reduction of structures borne noise is done in the following ways

1) Breaking the continuity by interposing layers of some acoustical insulators
2) Using double walls with air space between them
3) Using anti vibration mounts
4) Soft floor finish (carpet rubber etc)
5) Mechanical equipments such as refrigerators lifts fans etc. Produce vibrations in the structure. These vibrations can be checked by insulating the equipment properly

INSIDE NOISE:- The noise which are produced inside the hall or rooms in big offices are called as inside noises . They are produced due to machinery like air conditioners type writers in the hall.

CONCLUSION:- Acoustics of buildings is a very important fields. If proper care is not taken to achieve required acoustical properties in a building the building becomes unusable . Hence at the planning stage itself it is essential to take necessary to achieve optimum reverberation time.