APPLIED PHYSICS FOR CIVIL ENGINEERING (BPHYC102/202)
MODULE 1
OSCILLATIONS AND SHOCK WAVES

SYLLABUS

Module -I: Oscillations and Shock waves: Oscillations: Simple Harmonic motion (SHM), differential equation for SHM (No derivation), Sprigs: Stiffness Factor and its Physical Significance, series and parallel combination of springs(Derivation), Types of spring and their applications. Theory of damped oscillations (Qualitative), Types of damping (Graphical Approach). Engineering applications of damped oscillations, Theory of forced oscillations (Qualitative), resonance, and sharpness of resonance. Shock waves: Mach number and Mach Angle, Mach Regimes, definition and characteristics of Shock waves, Construction and working of Reddy shock tube, Applications of Shock Waves, Numerical problems.

Pre requisites: *Basics of Oscilations*

Self-learning*:Simple Harmonic motion, differential equation for SHM*

Oscillations and vibrations play a more significant role in our lives than we realize. When you strike a bell, the metal vibrates, creating a sound wave. All musical instruments are based on some method to force the air around the instrument to oscillate. Oscillations from the swing of a pendulum in a clock to the vibrations of a quartz crystal are used as timing devices. When you heat a substance, some of the energy you supply goes into oscillations of the atoms. Most forms of wave motion involve the oscillatory motion of the substance through which the wave is moving. Despite the enormous variety of systems that oscillate, they have many features in common with the simple system of a mass on a spring. The harmonic oscillators have close analogy in many other fields; mechanical example a weight on a spring, oscillations of charge flowing back and forth in an electrical circuit, vibrations of a tuning fork, vibrations of electrons in an atom generating light waves, oscillation of electrons in an antenna etc.,

Periodic Motion: Periodic motion is any motion that repeats itself in equal intervals of time.
Examples:

- a swing in motion
- a vibrating tuning fork
- the Earth in its orbit around the Sun
- simple pendulum

A special type of periodic motion is **simple harmonic motion**

Simple Harmonic Motion: SHM is the type of periodic motion in which the net restoring force F acting on the body is proportional to the displacement x from the equilibrium position and is directed opposite to the displacement, i.e., towards the equilibrium point. The body performing SHM is known as a simple harmonic oscillator (SHO).

There are two types of SHM

1. Linear SHM

Eg: 1. The vertical oscillations of a loaded spring suspended from a rigid support.

2. Motion of needle of sewing machine

2. Angular SHM

Eg : 1. Motion of pendulum

2. Vibration of tuning fork

Characteristics of SHM:

1. Motion must be periodic.
2. The acceleration developed in the motion due to the restoring force is directly proportional to its displacement from the equilibrium position.
3. The Force or acceleration is always directed opposite to the displacement i.e., towards the mean position (F α -x or F = – kx). The displacement can be represented by a sine or cosine function such as

   $x = a\ sin\omega t$, where, a is the amplitude and ω is the angular frequency.
4. The velocity of the body is maximum at the centre and minimum at extreme position.

Concepts of Simple Harmonic Motion (S.H.M):

Displacement (x): The distance covered by the body in SHM from its mean position.

Amplitude (a): The maximum displacement of the body from its equilibrium position or mean position is its amplitude.

Period (T): The time taken by the body to complete one oscillation is its period.

$$T = \frac{2\pi}{\omega}$$

Frequency (ν): Frequency of S.H.M. is the number of oscillations that a oscillating body performs per unit time.

$$\boldsymbol{\nu} = \frac{1}{T}$$

$$\boldsymbol{\nu} = \frac{\omega}{2\pi}$$

$$\omega = 2\pi\boldsymbol{\nu}$$

Angular frequency (ω): It is the angular displacement per unit time.

$$\omega = \frac{angle\ covered}{time\ taken} = \frac{2\pi}{T} = 2\pi\nu$$

Derivation of differential equation of SHM starting from Hooke's Law:

Consider a body of mass 'm' executing simple harmonic motion. Let the restoring force be F and the displacement of the body from its equilibrium position be *'x'*.

Then, for an oscillating body,the restoring force is directly proportional to the displacement from the mean position.

i.e., F = – kx --------(1)

which is commonly known as Hooke's Law where 'k' is the spring constant or force constant, [i.e. the restoring force/unit displacement]. The negative sign shows that restoring force acts in the direction opposite to the displacement 'x'.

The system must also obey Newton's second law of motion which states that the force is equal to mass 'm' times acceleration 'a', i.e. F = ma.

F = ma

$$F = m\frac{dv}{dt}$$

$F = m\frac{d^2x}{dt^2}$-----------(2)

Equating (1) and (2)

$$m\frac{d^2x}{dt^2} = -kx$$

$$\frac{d^2x}{dt^2} + \boldsymbol{\frac{k}{m}x = 0}$$

This equation is called as differential equation of SHM.

Solution of this equation is $x = a\sin wt$. where, 'a' is the amplitude and 'ω' is the angular frequency and 't' is the time elapsed. 'ω' is also called as natural frequency of vibration and is given as $\omega = \sqrt{\frac{k}{m}}$

The Time period & Frequency of oscillation: The time period of oscillation of a spring is dependent on the spring constant of the spring and the mass of the system. It is independent of the force of gravity. It is given by

$$T = \frac{2\pi}{\omega}$$

$$T = 2\pi\sqrt{\frac{m}{k}} \text{where} \omega^2 = \frac{k}{m}$$

And **frequency** is given by, $\nu = \frac{1}{T} = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$

Sprigs

Stiffness Factor and its Physical Significance

Physically, force constant is a measure of stiffness. In the case of springs, it represents how much force it takes to stretch the spring over a unit length. If the spring is strong or stiff, spring constant **k** will be large, and **k** will be small for a weak spring.

Expression for spring Constant for series combination of springs:

Consider two idealized springs with force constants k_1 and k_2 connected in series as shown in the figure. Let a body of load F = mg is suspended at the free end of these two springs in series combination. When the body is pulled downwards through a little distance 'x' , the two springs suffer different extensions say 'x_1' and 'x_2'. But the restoring force is same in each spring.

Following Hook's law, for the spring 1,

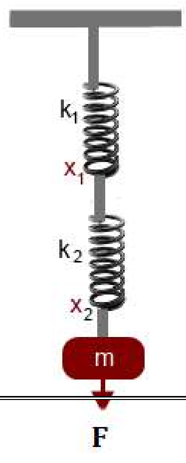
$F = -k_1x_1$

$mg = -k_1x_1$

or, $x_1 = -\frac{mg}{k_1}$ -----(1)

Similarly, for he spring 2,

$F = -k_2x_2$



$mg = -k_2x_2$

or, $x_2 = -\frac{mg}{k_2}$ -----(2)

For the combination,

$F = -k_sx$

$mg = -k_sx$

or, $x = -\frac{mg}{k_s}$-----(3)

But, the total extension, $x = (x_1 + x_2)$

Or, $-\frac{mg}{k_s} = -\frac{mg}{k_1} - \frac{mg}{k_2}$

$$\frac{1}{k_s} = \frac{1}{\mathrm{k}_1} + \frac{1}{\mathrm{k}_2}$$

Or, $\boldsymbol{k_s = \frac{k_1k_2}{k_1+k_2}}$

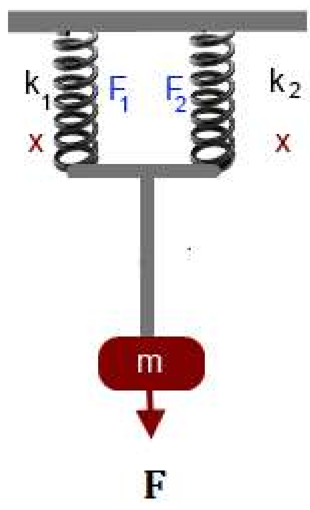
The time period is given as $\boldsymbol{T = 2\pi\sqrt{\frac{m}{k_s}}}$

Expression for spring Constant for parallel combination of springs:

Consider two idealized springs with force constants k_1 and k_2 connected in parallel as shown in figure. Let a body of load F = mg is suspended by these two springs in parallel combination. Let the body be pulled downwards through a small distance ‘x’. Each spring gets stretched by a length ‘x’. If F_1 and F_2 are the two restoring forces set up due to extension of springs, then

from Hook’s law, for the spring 1,

$F_1 = -k_1x$-----(1)



Similarly, for the spring 2,

$F_2 = -k_2x$-----(2)

∴For the combination,

$F_p = -k_px$-----(3)

The restoring force F_p is shared by the two springs.

Therefore,

$F_p = \mathrm{F}_1 + \mathrm{F}_2$

$-k_px = -\mathrm{k}_1\mathrm{x} - \mathrm{k}_2\mathrm{x}$

Or $k_p = \mathbf{k_1} + \mathbf{k_2}$

The time period is given as $T = 2\pi\sqrt{\frac{m}{k_p}}$

Different types of springs

Helical Springs

Helical springs are the most common types of springs in product manufacturing. Wire coiled into a helix shape (hence the name) with different cross-sections can make helical springs. Below are the kinds of springs under category one.

1. Compression Springs

Compression springs are open-coil helical springs with a constant coiled diameter and variable shape that resists axial compression. The simplest example of its application is in the ballpoint pen, where it is responsible for the "popping" effect. It is also applicable in valves and suspension.

2. Extension Springs

Unlike compression springs, extension springs are closed coil helical springs. They are suitable for creating tension, storing the energy, and using the energy to return the spring to its original shape. A simple example of its applications is in garage doors. Others are in pull levers, jaw pliers, and weighing machines.

3. Torsion Springs

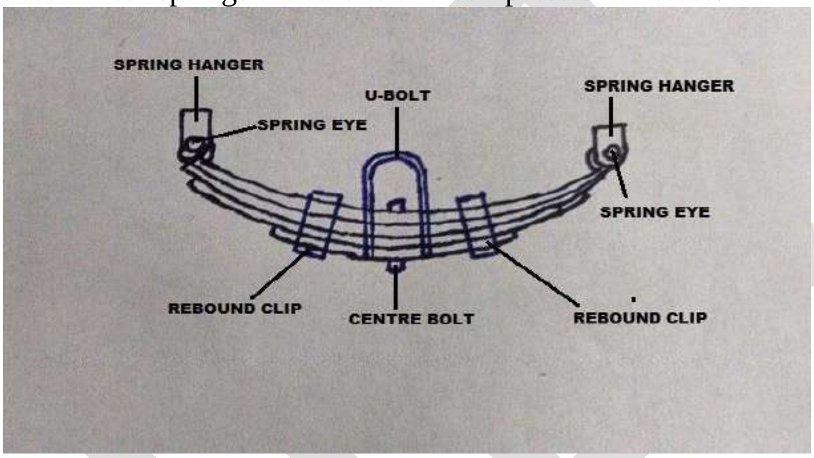
A torsion spring is attached to two different components using its two ends. This keeps the two components apart at a certain angle. These springs use radial direction when force is acting radially due to rotation.

Shock Absorber

A shock absorber is a mechanical or hydraulic device designed to absorb and damp shock impulses. This is achieved by converting the kinetic energy of the shock into another form of energy (typically heat) which is then dissipated. Shock absorber is to absorb or dampen the compression and rebound of the springs and suspension. Coil-over-shock absorber or spring coil shock absorber. Absorber with coil spring looks like a suspension strut.It helps to control unwanted and excess spring motion.

Leaf Springs (flat spring or carriage spring)

Leaf springs are types of springs made from rectangular metal plates, also known as leaves. The rectangular metal plates are normally bolted and clamped, and they have major use in heavy vehicles. Below are the different types of leaf springs and their applications. These are mostly used in automobiles. The major stresses produced in leaf springs are tensile and compressive stresses.



Application in railway/truck suspension

The main function of leaf springs in railways/truck suspension is to provide comfort to the passengers by minimizing the vertical vibration caused by the nonuniformity of road geometry. Leaf springs support the weight of the chassis, making them ideal for commercial vehicles. They also control axle damping. The chassis roll can be controlled more efficiently due to the high rear moment centre and wide spring base. If the springs are mounted wider apart, the roll tendencies will be less.

Different cases of SHM: Under SHM, we have the following 3 cases

1. Free oscillations
2. Damped oscillations
3. Forced oscillations

Free Oscillation: 'If an oscillating body oscillates with constant amplitude at its own natural frequency without the help of any external force is called free oscillation.

Natural Frequency: The natural frequency is the rate at which an object vibrates when it is not disturbed by an outside force.

Examples for free oscillations:

1. The vertical oscillations of a loaded spring suspended from a rigid support.
2. Motion of needle of sewing machine
3. Motion of pendulum
4. Vibration of tuning fork

Equation of motion for free oscillations:

The equation of motion of a free oscillation is given by

$$\frac{d^2x}{dt^2} + \frac{\mathrm{k}}{\mathrm{m}}\mathrm{x} = 0$$

Where, *m* is the mass of the oscillating body, *k* is the force constant, *x* is the displacement at the instant *t* of an oscillating body.

Damped Oscillation: The oscillations of a body whose amplitude goes on decreases with time due to the presence of resistive forces is called damped oscillation.

Examples:

1. Mechanical oscillations of a simple pendulum
2. A swing left free to oscillate after being pushed once.

Theory of damped oscillations:

Consider a body of mass 'm' executing oscillations in a resistive medium. The oscillations are damped due to resistance offered by the medium.

The damping force, acts in a direction opposite to the movement of the body and velocity dependent

i.e.,

$F_{dam} \alpha -v$

$F_{dam} = -bv$, where 'b' is damping constant

$$F_{net} = F_{res} + F_{dam}$$

$$F_{net} = -kx - bv$$

$$F_{net} = -kx - b\frac{dx}{dt}$$

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = 0$$

$$\frac{d^2x}{dt^2}+\left(\frac{b}{m}\right)\frac{dx}{dt}+\left(\frac{k}{m}\right)x=0 \text{-------(1)}$$

Where, $2\beta=\frac{b}{m}$ $\beta=\frac{b}{2m}$, $\omega^2=\frac{k}{m}$

$$\frac{d^2x}{dt^2}+2\beta\frac{dx}{dt}+\omega^2x=0 \text{----------(2)}$$

The solution of the above equation is

$x=Ae^{\alpha t}$ --------(3) where, 'A' and 'α' are constants

$$\frac{dx}{dt}=A.\alpha.e^{\alpha t}=\alpha.x$$

$$\frac{d^2x}{dt^2}=A.\alpha.\alpha e^{\alpha t}=\alpha^2.x$$

$$\alpha^2x+2\beta.\alpha x+\omega^2x=0$$

$$x(\alpha^2+2\beta.\alpha+\omega^2)=0$$

$$\Rightarrow(\alpha^2+2\beta.\alpha+\omega^2)=0$$

The solution of this equation can be given using

$$\alpha=\frac{-b\pm\sqrt{b^2-4ac}}{2a}$$

$$\alpha=\frac{-2\beta\pm\sqrt{4\beta^2-4\omega^2}}{2}$$

$$\alpha=\frac{-2\beta\pm2\sqrt{\beta^2-\omega^2}}{2}$$

$$\alpha=-\beta\pm\sqrt{\beta^2-\omega^2} \text{ -------(4)}$$

(4) in (3)

$$x=Ae^{\left(-\beta\pm\sqrt{\beta^2-\omega^2}\right)t}$$

Or, $x=A_1e^{\left(-\beta+\sqrt{\beta^2-\omega^2}\right)t}+A_2e^{\left(-\beta-\sqrt{\beta^2-\omega^2}\right)t}$ -------(5)

Where, A_1 and $A_2$are constants to be evaluated

Now, at t=0, $x = x_0$ (i.e., maximum displacement)

∴equation (5) becomes $x_0 = A_1 + A_2$ -------(6)

Also, at t=0, $x = x_0$, the velocity is zero. i.e.,$\frac{dx}{dt} = 0$

$$\therefore \frac{dx}{dt} = \left(-\beta + \sqrt{\beta^2 - \omega^2}\right) A_1 e^{\left(-\beta + \sqrt{\beta^2 - \omega^2}\right)t} + \left(-\beta - \sqrt{\beta^2 - \omega^2}\right) A_2 e^{\left(-\beta - \sqrt{\beta^2 - \omega^2}\right)t} = 0$$

Since t=0,

$$\left(-\beta + \sqrt{\beta^2 - \omega^2}\right) A_1 + \left(-\beta - \sqrt{\beta^2 - \omega^2}\right) A_2 = 0$$

$$-\beta(A_1 + A_2) + \sqrt{\beta^2 - \omega^2}\,(A_1 - A_2) = 0$$

$$-\beta x_0 + \sqrt{\beta^2 - \omega^2}\,(A_1 - A_2) = 0$$

$$\frac{\beta x_0}{\sqrt{\beta^2 - \omega^2}} = A_1 - A_2 \text{ -------(7)}$$

Adding (6) and (7)

$$2A_1 = x_0 + \frac{\beta x_0}{\sqrt{\beta^2 - \omega^2}}$$

$$2A_1 = x_0 \left(\frac{1 + \beta}{\sqrt{\beta^2 - \omega^2}} \right)$$

$$\boxed{A_1 = \frac{x_0}{2} \left(1 + \frac{\beta}{\sqrt{\beta^2 - \omega^2}} \right)} \qquad \text{----------(8)}$$

Subtracting, (6) - (7)

$$2A_2 = x_0 - \frac{\beta x_0}{\sqrt{\beta^2 - \omega^2}}$$

$$2A_2 = x_0 \left(1 - \frac{\beta}{\sqrt{\beta^2 - \omega^2}} \right)$$

$$A_2 = \frac{x_0}{2}\left(1-\frac{\beta}{\sqrt{\beta^2-\omega^2}}\right) \text{-------(9)}$$

$\therefore$ Equation (5) is given as

$$\boxed{x = \frac{x_0}{2}\left(1+\frac{\beta}{\sqrt{\beta^2-\omega^2}}\right).e^{\left(-\beta+\sqrt{\beta^2-\omega^2}\right)t} + \frac{x_0}{2}\left(1-\frac{\beta}{\sqrt{\beta^2-\omega^2}}\right).e^{\left(-\beta-\sqrt{\beta^2-\omega^2}\right)t}} \text{--------(10)}$$

This is the expression for decay amplitude.

Depending upon the strength of damping force the quantity $(\beta^2-\omega^2)$ can be positive /negative /zero giving rise to three different cases.

We have the general equation of damped oscillation as (eqn (5))

$$x = A_1 e^{\left(-\beta+\sqrt{\beta^2-\omega^2}\right)t} + A_2 e^{\left(-\beta-\sqrt{\beta^2-\omega^2}\right)t}$$

Or, $x = e^{-\beta t}(A_1 e^{\left(\sqrt{\beta^2-\omega^2}\right)t} + A_2 e^{\left(-\sqrt{\beta^2-\omega^2}\right)t}$ ---------**

Case 1: If $\beta^2 > \omega^2$, over damping

When $\beta^2 > \omega^2$, $\sqrt{\beta^2-\omega^2}$ is positive.

Let $\alpha = \sqrt{\beta^2-\omega^2}$

Then the eqn ** becomes

$$x = e^{-\beta t}(A_1 e^{\alpha t} + A_2 e^{-\alpha t})$$

That means, there is an exponential decay of the displacement w.r.t time.

i.e., the body, without oscillating, returns from its maximum displacement to the equilibrium position very slowly and rests there. This is referred as over damped motion.

Eg: The motion of simple pendulum in a highly viscous medium.

Case 2 : If $\beta^2 = \omega^2$, critical damping

When $\beta^2 = \omega^2$,

Then the eqn ** will be

$$x = e^{-\beta t}(A_1 + A_2)$$

i.e., the body doesn't oscillate and returns to its equilibrium position very rapidly. This is referred as critical damping.

Critical damping provides the quickest approach to zero amplitude compared to other two cases.

Eg: The spring of the automobiles, the speedometers of the vehicles.

Case 3: If $\beta^2 < \omega^2$, under damping

When $\beta^2 < \omega^2$, $\sqrt{\beta^2 - \omega^2}$ is negative.

If $\sqrt{\beta^2 - \omega^2} = \omega_1$

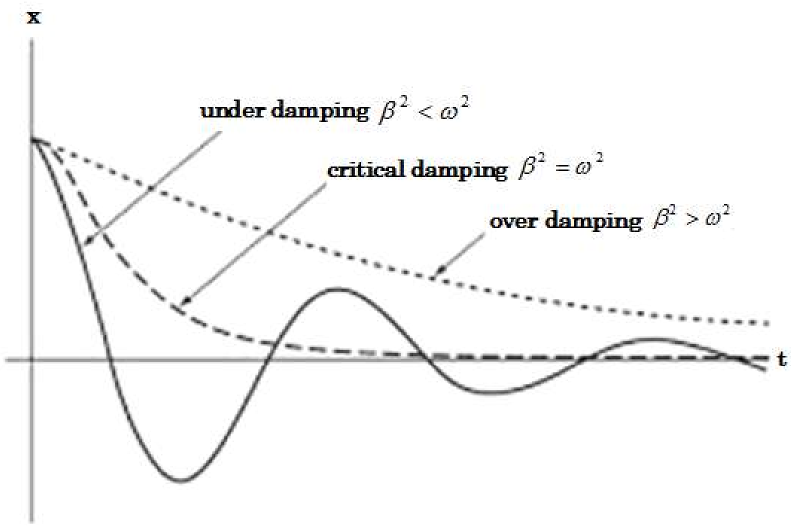
Then, $\sqrt{\omega^2 - \beta^2} = i\omega_1$

∴the eqn ** will be

$$x = e^{-\beta t}(A_1 e^{i\omega_1 t} + A_2 e^{-i\omega_1 t})$$

i.e., the amplitude of the oscillating system will not be constant and decreases exponentially with time, till the oscillation dies out. This is referred as under damping

Eg: The motion of simple pendulum in air.



Quality Factor& its significance: The rate of energy loss of a weakly damped harmonic oscillator is convenientlycharacterized bya single parameter Q, called the **quality factor of the oscillator.**

Quality factor is defined to be 2π timesthe energy stored in the oscillator divided by the energy lost in a single oscillation period.

$$Q = 2\pi \frac{Energy\ stored\ in\ the\ oscillator}{Energy\ Loss\ per\ period}$$

$Q = \frac{\omega}{2\beta}$, where, $= \frac{2\pi}{T}$, $2\beta = \frac{b}{m}$

Forced Oscillation: The oscillation in which a body oscillates under the influence of an external periodic force (also called as driving force) is known as forced oscillation.Here, the amplitude of oscillation, experiences damping but remains constant due to the external energy supplied to the system.

Eg: Oscillations of a swing which is pushed periodically by a person.

Theory of Forced Oscillations: Consider a body of mass 'm' executing oscillations in a damping medium, acted upon by an external periodic sinusoidal force '$Fsin\omega_o t$'. Then its equation of motion is

$$F_{net} = F_{res} + F_{dam} + F_{forced}$$

$$F_{net} = -kx - bv + F\sin\omega_o t$$

$$F_{net} = -kx - b\frac{dx}{dt} + F\sin\omega_o t$$

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = F\sin\omega_o t$$

$$\frac{d^2x}{dt^2} + \left(\frac{b}{m}\right)\frac{dx}{dt} + \left(\frac{k}{m}\right)x = \frac{F}{m}\sin\omega_o t$$

$$\frac{d^2x}{dt^2} + 2\beta\frac{dx}{dt} + \omega^2 x = \frac{F}{m}\sin\omega_o t \text{ ------(1)}$$

The solution of this equation is

$$x = a\sin(\omega_o t - \alpha) \text{ --------(2)}$$

Where, 'a' is the amplitude and $'\alpha'$ is the phase of the oscillating body to be determined.

$$\frac{dx}{dt} = a\omega_o\cos(\omega_o t - \alpha)$$

$$\frac{d^2x}{dt^2} = -a\omega_o\omega_o\sin(\omega_o t - \alpha)$$

$$\frac{d^2x}{dt^2} = -a\omega_o{}^2\sin(\omega_o t - \alpha)$$

$\therefore (1) \Rightarrow -a\omega_o^2 \sin(\omega_o t-\alpha)+2\beta a\omega_o \cos(\omega_o t-\alpha)+\omega^2 a\sin(\omega_o t-\alpha)=\frac{F}{m}\sin\omega_o t$

$\frac{F}{m}\sin(\omega_o t)$ can be written as $\frac{F}{m}\sin[(\omega_o t-\alpha)+\alpha]=\frac{F}{m}\left(\sin(\omega_o t-\alpha).\cos\alpha+\cos(\omega_o t-\alpha).\sin\alpha\right)$

$\therefore (1) \Rightarrow$

$$-a\omega_o^2 \sin(\omega_o t-\alpha)+2\beta a\omega_o \cos(\omega_o t-\alpha)+a\omega^2 \sin(\omega_o t-\alpha)=\frac{F}{m}\sin(\omega_o t-\alpha).\cos\alpha+\frac{F}{m}\cos(\omega_o t-\alpha).\sin\alpha$$

By equating the coefficients of $\sin(\omega_o t-\alpha)$ from both the sides, we get

$$-a\omega_o^2+a\omega^2=\frac{F}{m}.\cos\alpha$$

$$a(\omega^2-\omega_o^2)=\frac{F}{m}.\cos\alpha \text{ --------(2)}$$

Similarly, by equating the coefficients of $cos(\omega_o t-\alpha)$ from both the sides, we get

$$2\beta a\omega_o=\frac{F}{m}.\sin\alpha \text{ --------(3)}$$

Squaring and adding eqn (2) and (3) we get,

$$(a(\omega^2-\omega_0^2))^2+(2\beta a\omega_0)^2=\left(\frac{F}{m}\right)^2(\cos^2\alpha+\sin^2\alpha)$$

$$a^2\left[\left(\omega^2-\omega_0^2\right)^2+4\beta^2\omega_0^2\right]=\left(\frac{F}{m}\right)^2$$

$$a^2=\frac{\left(\frac{F}{m}\right)^2}{\left(\omega^2-\omega_0^2\right)^2+4\beta^2\omega_0^2}$$

$$\boxed{a=\frac{\left(\frac{F}{m}\right)}{\sqrt{\left(\omega^2-\omega_0^2\right)^2+4\beta^2\omega_0^2}}}$$

This equation represents the amplitude of the forced vibrations.

Phase of the forced vibrations:

Dividing eqn (3) by eqn (2)

$$\tan\alpha=\frac{2\beta a\omega_0}{a(\omega^2-\omega_0^2)}=\frac{2\beta\omega_0}{(\omega^2-\omega_0^2)}$$

$\therefore$the Phase of the forced vibration is given by

$$\boxed{\alpha = \tan^{-1}\left(\frac{2\beta\omega_0}{(\omega^2 - \omega_0^2)}\right)}$$

Dependence of amplitude and phase on the frequency of the applied force:

Case 1: $\omega_o \ll \omega$, when the frequency of the force is low.

For $\omega_o \ll \omega$, ω_o^2 will be very small and damping is small ($\beta \to 0$)

i.e.,$\omega^2 - \omega_o^2 \approx \omega^2 \; and \; 2\beta\omega_o \approx 0$

∴The amplitude,

$$a = \frac{\left(\frac{F}{m}\right)}{\omega^2} = \frac{F}{m\omega^2}$$

The Phase α is given as

$$\alpha = \tan^{-1}\left(\frac{2\beta\omega_0}{\omega^2 - \omega_0^2}\right)$$

since$\omega_o$is very small and damping $(\beta)$is also small

$$\omega^2 - \omega_o^2 \approx \omega^2 \; and \; \frac{2\beta\omega_o}{\omega^2} \approx 0$$

$$\therefore \alpha = \tan^{-1}(0)$$

$$\alpha = 0$$

This shows that the amplitude of vibration is independent of the frequency of force. The amplitude depends on the magnitude of the applied force. The displacement and force are always in phase.

Case 2: $\omega_o = \omega$, the frequency of force is equal to frequency of the body.

For $\omega_0 = \omega, \left(\omega^2 - \omega_0^2\right) = 0$

∴amplitude $a = \dfrac{F/m}{2\beta\omega_0} = \dfrac{F/m}{2\left(\frac{b}{2m}\right)\omega_0} = \dfrac{F}{b\omega_0}$

$$a = \frac{F}{b\omega_0}$$

The phase, $\alpha = \tan^{-1}\left(\dfrac{2\beta\omega_0}{0}\right)$

$$\alpha = \tan^{-1}(\infty) = \frac{\pi}{2}$$

This shows that the amplitude of vibration is governed by the damping and for small damping forces the amplitude of vibration is quite large. The displacement lags behind the force by $(\frac{\pi}{2})$.

Case 3: $\omega_o \gg \omega$, the frequency of force is greater than frequency of the body.

For $\omega_o \gg \omega$, and damping is small ($\beta \to 0$)

$$(\omega^2 - \omega_0^2)^2 \approx (\omega_o^2)^2$$

$$\therefore a = \frac{F/m}{\sqrt{4\beta^2\omega_0^2 + \left(\omega_0^4\right)}}$$

Since β is very small, $4\beta^2\omega_o^2 \langle\langle \omega_o^4$

$$a = \frac{F/m}{\sqrt{\omega_0^4}} = \frac{F/m}{\omega_0^2} = \frac{F}{m\omega_0^2}$$

The phase, $\alpha = \tan^{-1}\left[\frac{2\beta\omega_0}{\omega^2 - \omega_0^2}\right] = \tan^{-1}\left[\frac{-2\beta}{\omega_0}\right]$

Since β is very small $\frac{2\beta}{\omega_o} \approx 0$

$$\alpha = \tan^{-1}(-0) = \pi$$

In this case, the amplitude goes on decreasing and phase difference tends towards π.

Resonance

The amplitude of the forced vibrations is given as

$$a = \frac{\left(\frac{F}{m}\right)}{\sqrt{\left(\omega^2 - \omega_0^2\right)^2 + 4\beta^2\omega_0^2}} \text{ ---------(1)}$$

Conditions for resonance: For ‘a’ to be maximum, the denominator in the above equation must be minimum. It is possible when,

i) $\beta = \frac{b}{2m}$ is minimum, i.e., when the damping caused by the medium is made minimum.

ii) $\omega_o = \omega$, i.e., when frequency of the applied force (ω_o) becomes equal to the natural frequency of vibration of the body (ω).

Therefore eqn (1) reduces to

$$a = \frac{\left(\frac{F}{m}\right)}{\sqrt{4\beta^2\omega^2}} = \frac{\left(\frac{F}{m}\right)}{2\beta\omega} \quad \text{--- (2)}$$

This is the expression for maximum amplitude (resonance).

"When the frequency of periodic force acting on a vibrating body is equal to the natural frequency of vibrations of the body, the body vibrates with maximum amplitude. This phenomenon is called resonance".

At resonance, the energy transfer from the periodic force to the vibrating body is maximum.

Eg: 1. Helmholtz resonator,

2. the vibrations caused by an excited tuning fork in another nearby identical tuning fork.

Sharpness of resonance: -

The amplitude is maximum at resonance frequency which decreases rapidly as the frequency increases or decreases from the resonant frequency.

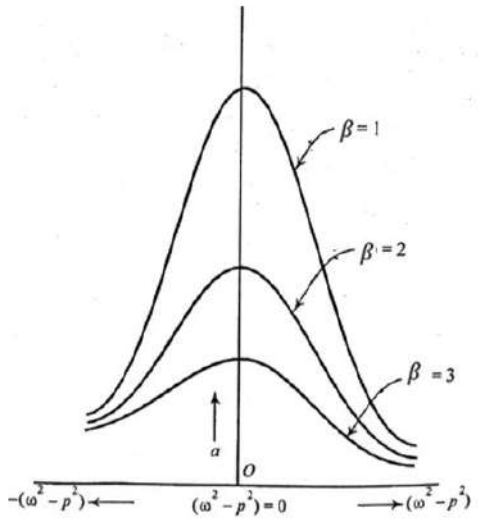
The rate at which the amplitude decreases with the frequency of the applied external force on either side of resonant frequency is termed as "sharpness of resonance".

$$\boldsymbol{Sharpness\ of\ resonance = \frac{change\ in\ amplitude}{change\ in\ frequency}}$$

Note: The sharpness of a resonance is measured by its Q-factor.

Significance of sharpness of resonance: The rate at which the change in amplitude occurs near resonance depends on damping. For small damping, the rate is high and the resonance is said to be sharp. For heavy damping it will be low, and resonance is said to be flat.

Effect of damping: The response of amplitude to various degrees of damping is as shown in the graph. From the graph, it can be observed that, for larger values of damping coefficient 'β', the curve is flat and hence the resonance is flat. On the other hand, for smaller values of damping coefficient β the curve is sharp and it refers to sharp resonance.



SHARPNESS OF RESONANCFE

The sharpness of resonant peak depends on the damping. If the damping is small, the resonant peak is sharp, if the damping is large, it is less sharp.

****

Shock waves

In Aerodynamics, the speed of the bodies moving in a fluid medium can be classified into different categories on the basis of following terms

Mach number: it is defined as ratio of the speed of the object to the speed of the sound in a given medium. i.e.,

$$\boldsymbol{Mach\ number = \frac{object\ speed}{speed\ of\ the\ sound\ in\ a\ given\ medium}}$$

It is denoted as M. If v is the speed of object and 'a' is the speed of sound in the medium ,

then $\mathbf{M = \frac{v}{a}}$ and speed of the sound is given by $\mathbf{a=\sqrt{\gamma RT}}$

γ – ratio of specific heats

R – specific gas constant

T – local temperature in Kelvin

Mach number gives a measure of how fast a body is moving with respect to the speed of sound. It is a very important quantity in compressible flow theory (where density of the fluid changes).

Acoustic, ultrasonic (based on frequency), Subsonic, Supersonic waves

1) **Acoustic wave**

   Acoustic wave is simply a sound wave which moves with the speed of 330m/s, in air at STP. they have frequencies between 20 -20,000 Hz. Amplitude of acoustic wave is very small.

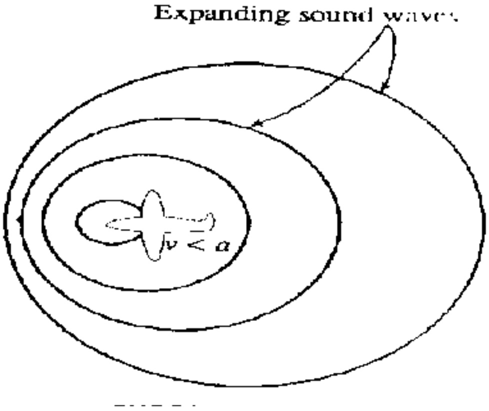
2) Ultrasonic waves

   These are pressure waves having frequencies beyond 20,000 Hz. but they travel with the same speed as that of sound. Amplitude of ultrasonic wave is very small.

Mach number regimes

1) **Subsonic waves**

If the speed of mechanical wave or body moving in a fluid is lesser than that of sound. Then, such a speed is referred to as subsonic and the wave is subsonic wave. All the subsonic waves have Mach number less than 1. For a body moving with subsonic speed sound emitted by it manages move ahead and away from the body since it is faster than the body.



Eg : speed of car and train

2) Supersonic waves

Supersonic waves are mechanical waves which travel with speeds greater than that of sound i.e., with speeds for which Mach no. >1. A body with supersonic speed moves ahead leaving behind series of expanding sound waves. Amplitude of supersonic wave will be very high and it effects medium in which it is travelling.

Eg: fighter planes.

3) Transonic: As the speed of the object approaches the speed of sound, the flight Mach number is nearly equal to one, **M = 1**, and the flow is said to be transonic. At some places on the object, the local speed exceeds the speed of sound.

4) Hypersonic: For speeds greater than five times the speed of sound, **M > 5**, the flow is said to be hypersonic. At these speeds, some of the energy of the object now goes into exciting the chemical bonds which hold together the nitrogen and oxygen molecules of the air.

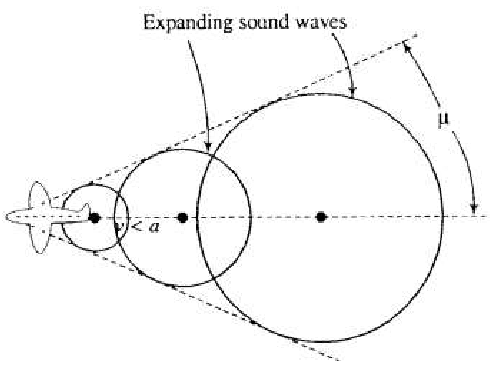
Mach cone

A number of common tangents drawn to the expanding sound waves emitted from a body at supersonic speed constitute a cone called Mach cone.

Mach angle

The angle made by the tangent with the axis of the Mach cone is called the Mach angle (μ)

$\mu = \sin^{-1}(\frac{1}{M})$ where M is the Mach number.



Shock waves
Any fluid that propagates at supersonic speeds gives rise to shock wave.

- Shock waves are produced by a sudden dissipation of mechanical energy in a medium enclosed in a small space. The Shock waves depends on pressure, temperature and density of the medium through which it propagates.
- Ex: Shock waves are produced in nature during earth quakes called Seismic waves (2km/s – 8km/s)

There are two kinds of shock waves

1) Strong Shock waves: It is a compressed region possessing very high pressure and temperature having Mach number greater than 1

Ex: Lighting thunder or bombing, etc.,

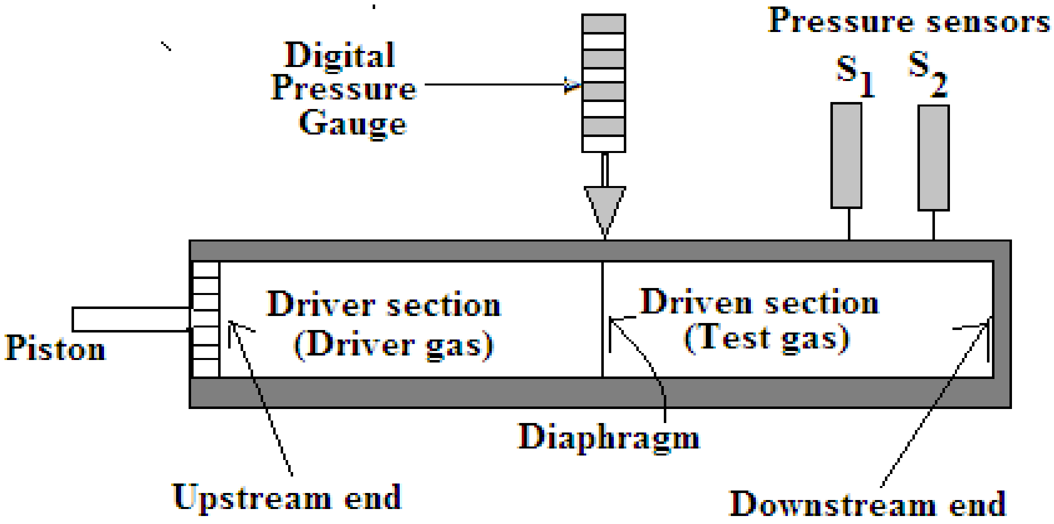
2) Weak Shock waves: It is a compressed region possess Low pressure and temperature having Mach number less than or closer to 1

Ex: Explosion of a Cracker, Bursting of aTyre, etc.,

Properties of shock waves:
1) They travel in the medium with Mach number exceeding 1.
2) Shock waves obey the laws of fluid mechanics.
3) The effect caused by the shock waves result in increase of entropy.
4) Across the shock wave supersonic flow is decelerated into subsonic flow.
5) Shock wave exists in a very thin space of thickness not exceeding one micro meter.

Reddy tube or Reddy shock tube

Reddy tube is hand operated shock tube capable of producing shock waves by using human energy. It is a long cylindrical tube with two sections separated by a diaphragm. Its one end is fitted with the piston and the other end is closed or open to the surroundings.



REDDY TUBE

Description

- Reddy tube consists of a cylindrical stainless steel tube of about 30mm diameter. And of length nearly 1 m.
- It is divided into 2 sections each of length about 50 cm. one is the **driver tube** other is **driven tube** separated by a 0.1mm thick aluminum or paper diaphragm.
- It has a piston fitted at the far end of the driver section. Whereas the end of the driven section is closed.
- A digital pressure gauge is mounted in the driver section next to the diaphragm.
- Two piezoelectric sensors S_1 and S_2 are mounted on the driven section.
- The driver section is filled with gas termed as driver gas (high pressure) and the gas in the driven section is termed **driven gas.**

Working:

- The driver gas is compressed by pushing the piston hard into the driver tube until the diaphragm ruptures.
- Following the rupture, the driver gas rushes into the driven section and pushes the driven gas towards the downstream end which generates a moving shock wave that traverses the length of the driven section.
- The shock wave instantaneously raises the temperature and the pressure of the driven gas.
- If 'x' and 't' is the distance travelled and time taken by the shock waves between the two sensors, then velocity of shock waves traveling between the two sensors are given by $v = \frac{x}{t}$ and Mach number can be calculated as $M = \frac{v}{a}$

Characteristics of a Reddy's tube.

- The Reddy's tube operates on the principle of free piston driven shock tube(FPST)
- It is a hand operated shock producing device
- It is capable of producing Mach no exceeding 1.5
- The rupture pressure is a function of the thickness of the diaphragm
- Temperatures exceeding 900 K can ben be easily obtained by the reddytube. By using He as the driver gas and Ar as the driven gas.

Applications of shock waves

1. Cell information

By passing shock wave of suitable strength, DNA can be pushed inside a cell without affecting the functionality of DNA. This has wide biological applications.

2. Wood preservation

By using shock waves, chemical preservatives in the form of solutions could be pushed into the interior of wood samples which helps in withstanding the microbial attacks. By this method the life of ordinary wood can be increased.

3. Use in Pencil Industry:

In the manufacture of pencils, in the industry, the wood needs to be softened by soaking it in a polymer at 700C for about 3 hours and then dried. It takes days for the wood to dry.
In the modern process, the liquid is passed into the wood almost instantaneously by placing it in a liquid and sending a shock wave. The wood is then taken out and it will not take longer time to dry. The treated wood is ready for the next process without any delay.

4. Kidney stone treatment:

Shock wave is used in a therapy to crush the kidney stones into smaller pieces after which, they are passed out of the body smoothly through the urinary tracts.

5. Gas dynamics studies:

The extreme conditions of pressure and temperature that can be produced in the shock tube, helps us to the study of high temperature gas dynamics. This knowledge is useful in the study of supersonic motion of bodies & hypersonic re-entry of space vehicles into the atmosphere.

6. Shock wave assisted needleless drug delivery:

By using shock waves, drugs can be injected into the body without using needles. The drug is filled into a cartridge which is kept pressed on the skin & the shock wave is sent into the body using high pressure. The drug enters the body directly through pores of the skin. In this process, the patients do not experience any pain.

7. Treatment of dry bore wells:

Water will be available in the bore wells when water accumulates in the bore well through a number of seepage points which are porous. Sometimes, such seepage points are blocked by sand particles. A shockwave sent through such a dry bore well, clears the blockages and makes the bore well into a water source.

Numerical problem

1) The distance between the two pressure sensors in a shock tube is 100mm. The time taken by a shock wave to travel this distance is 200 microseconds. If the velocity of sound under the same conditions is $340ms^{-1}$, find the Mach number of the shock wave. (4 marks)

QUESTIONS:

1. Define simple harmonic motion, Mention the characteristics of SHM, Derive the equation for simple harmonic motion using Hooke's law.
2. Obtain the expression for period of oscillations of two springs in series and parallel combination.
3. What are damped oscillations? Give the theory of damped oscillations and hence discuss the case of under damping.
4. Give the theory of forced oscillations.
5. Define shock waves. Explain the experimental method of producing shock waves and measuring its Mach number using Reddy Shock tube.
6. Define Mach Number. Distinguish between subsonic, supersonic and hypersonic waves.

NUMERICALS

1) A mass of $25x10^{-2}$ kg is suspended from the lower end of vertical spring having a force constant 25N/m. What should be the damping constant of the system so that motion is critically damped?
2) A spring undergoes an extension of 5 cm for a load of 50 g. Find its force constant, angular frequency and frequency of oscillation, if it is set for vertical oscillations with a load of 200 g attached to its bottom. Ignore the mass of the spring.
3) A free particle is executing SHM in a straight line with a period of 25 seconds, after 5 seconds it has crossed the equilibrium point, the velocity is found to be 0.7m/s. find the displacement at the end of 10 seconds, and also the amplitude of oscillations.
4) The distance between the two pressure sensors in a shock tube is 100mm. The time taken by a shock wave to travel this distance is 200 microsecond. If the velocity of sound under the same conditions is $340ms^{-1}$, find the Mach number of the shock wave.

5) A mass of 0.5kg causes an extension of 0.003m in a spring and the system is set for oscillations. Find i) The force constant for the spring ii) Angular frequency and iii) Time period of the resulting oscillation.
6) Calculate the peak amplitude of vibration of system whose natural frequency is 1000Hz when it oscillates in a resistive medium for which the value of damping/unit mass is 0.008rad/s under the action of an external periodic force /unit mass of amplitude 5N/kg, with tunable frequency.

****

MODULE 2 - ELASTICITY

Stress-Strain Curve, Stress hardening and softening. Elastic Moduli, Poisson's ratio, Relation between Y, n and σ (with derivation), mention relation between K, Y and σ, limiting values of Poisson's ratio. Beams, Bending moment and derivation of expression, Cantilever and I section girder and their Engineering Applications, Elastic materials (qualitative). Failures of engineering materials - Ductile fracture, Brittle fracture, Stress concentration, Fatigue and factors affecting fatigue (only qualitative explanation), Numerical problems.

The study of strength of materials is to provide the means of analysing and designing various machines and load bearing structures.

Elasticity: The property of material body to regain its original shape and size on removal of the deforming forces is called elasticity. Within certain elastic limit steel and quarts show elastic properties. The elastic property is desirable for materials used in tools and machines.

Plasticity: Bodies which does not show any tendency to recover their original condition are said to be Plastic and the property is called plasticity. Eg – polyethylene, Polystyrene etc
This property of the material is necessary for forging, stamping images on coins and ornamental works.

Load: The term load implies the combination of external forces acting on a body and its effect is to change the form or the dimensions of the body. It is essentially a deforming force.

Stress: The restoring force per unit area developed inside the body is called stress.
The magnitude of the restoring force is exactly equal to that of the applied force, **stress is given by the ratio of the applied force to the area of its application**
Stress = $\frac{Restoring\ Force}{cross\ sectiponal\ area} = \frac{F}{A}$, S I unit of stress is N/m^2.

<u>Concept of strain</u>: When a body is subjected to external force, there will be change in dimensions of the body. The change in dimension is called deformation. **The ratio of change in dimension of body or deformation to the original dimension of the body is called known as strain.** Strain $= \frac{change\ in\ dimension\ of\ the\ body}{original\ dimension} = \frac{\delta L}{L}$

Hooke's law Hooke's law states that when a material is loaded within its elastic limit, stress is directly proportional strain. It means that the ratio of stress to strain is constant within the elastic limit. This constant is known as Modulus of elasticity .

$$\frac{stress}{strain} = \text{constant or modulus of elasticity}$$

STRESS-STRAIN CURVE

Typical stress strain curve for a metal is shown in Fig. 1.3. This graph is plotted between the stress (which is equal in magnitude to the applied force per unit area) and the strain produced.

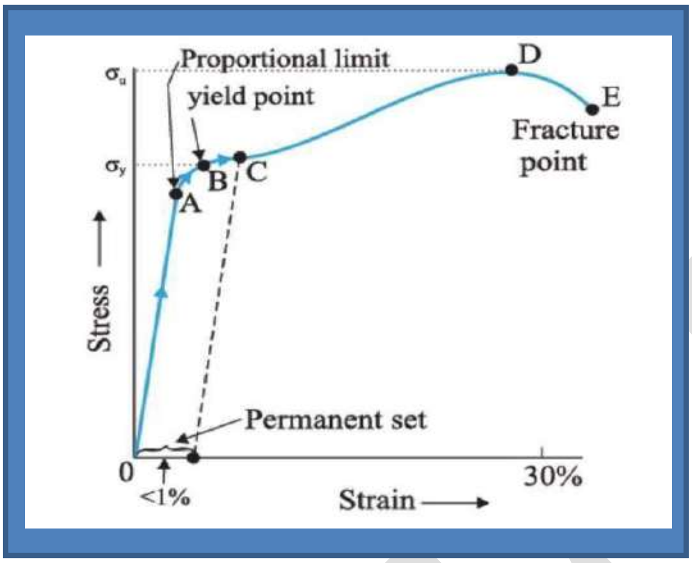


Fig. 1.3 A typical stress-strain curve for a metal

- The curve is linear in the region between O to A (Hooke's law is obeyed in this region and body behaves as elastic). The relationship between stress and strain in this initial region is not only linear but also proportional. Beyond point A, the proportionality between stress and strain no longer exists; hence the stress at A is called the proportional limit.
- With an increase in stress beyond the proportional limit, the strain begins to increase more rapidly for each increment in stress. Consequently, the stress-strain curve has a smaller and smaller slope, until, at point B, the curve becomes horizontal.
- Point B is the yield point (also known as elastic limit) and the corresponding stress is yield strength (σ_y) of the material.
- Above point B the strain increases rapidly even for a small change in the stress (The portion between B and D). In this region the body does not regain its original dimension and when the stress is made zero, the strain is not zero. Thus the material is said to have a permanent set and the deformation is said to be plastic deformation (See Fig. 1.3).
- After the point D, additional strain is produced even by a small applied force and fracture occurs at point E (See Fig. 1.3).
- The ratio of stress and strain, in the proportional region within the elastic limit of the stress strain curve (region OA in Fig. 1.3) is called modulus of elasticity and is characteristic of the material.
- It is of great importance to know the elastic limit for applications so that we can avoid the region of plastic deformation which may create problems in designing devices.

Strain hardening and strain softening

Strain hardening (also called work-hardening or cold-working) is the process of making a metal harder and stronger through plastic deformation. When a metal is plastically deformed, dislocations move and additional dislocations are generated. The more dislocations within a material, the more they will interact and become pinned or tangled. This will result in a decrease in the mobility of the dislocations and a strengthening of the material.

Strain softening: When the material is loaded either in tension or in compression, strain will build up with the applied stress. When it reaches the peak stress (for your case - yielding in tension) the material drops its shear resistance due to the continuous plastic deformation. This behaviour is called **strain softening.**

FACTOR OF SAFETY

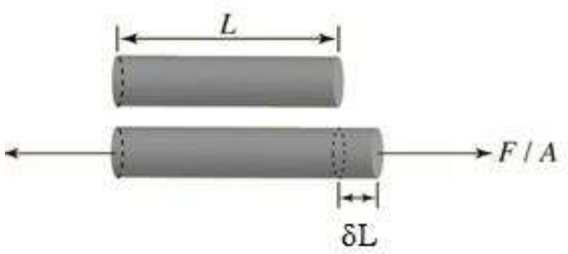
To avoid permanent deformation due to maximum stress, the engineering tools are to be used within the elastic limit with a working stress.

Factor of safety = Breaking stress / Working stress

Types of Elastic Moduli:

1. **Young's Modulus of Elasticity (Y)**

When a wire is acted upon by two equal and opposite forces in the direction of its length, the length of the body is changed. The change in length per unit length ($\delta L/L$) is called the longitudinal strain and the restoring force (which is equal to the applied force in equilibrium) per unit area of cross-section of wire is called the longitudinal stress.



For small change in the length of the wire, the ratio of the longitudinal stress to the corresponding strain is called the **Young's modulus of elasticity (Y)** of the wire. Thus,

Y = Longitudinal stress / Linear Strain = $\frac{(F|A)}{(\partial l|l)} = \frac{Fl}{A\partial l}$

Let there be a wire of length 'l' and radius 'r'. It's one end is clamped to a rigid support and a mass M is attached at the other end. Then

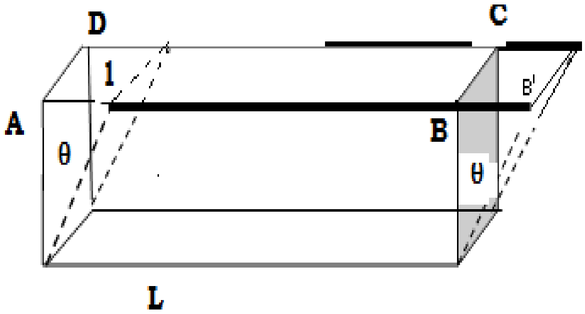
$F = Mg$ and $A = \pi r^2$

Substituting in above equation, we have, $Y = \frac{Mgl}{(\pi r^2)\delta l}$.

2. Modulus of Rigidity (n) When a body is acted upon by an external force tangential to a surface of the body, the opposite surfaces being kept fixed, it suffers a change in shape of the body, its volume remains unchanged. Then the body is said to be sheared. The tangential force acting per unit area of the surface is called the **'shearing stress' (F/A).**

The ratio of displacement to perpendicular distance between the two surfaces is known as **shearing strain (θ)**.

Shearing strain $\theta = \frac{l}{L}$ when θ is small.



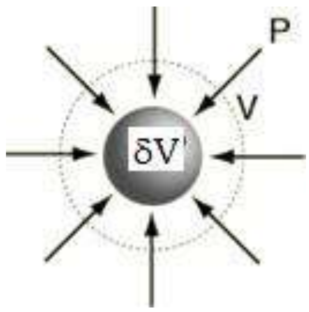
For small strain, the ratio of the shearing stress to the shearing strain is called the **'modulus of rigidity'** of the material of the body. It is denoted by 'n'.

Rigidity modulus (n) = Tangential stress / shear Strain

$$\mathbf{n} = \frac{F/A}{\theta} = \frac{F}{A\theta}$$

3. Bulk Modulus of Elasticity (K)

Describes volumetric elasticity or the tendency of an object to deform in all directions when uniformly loaded in all directions; it is defined as volumetric stress over volumetric strain, and is the inverse of compressibility. K = Volumetric stress / Volume strain $= \frac{FV}{A\delta V}$.



When a uniform pressure (normal force) is applied all over the surface of a body, the volume of the body changes. The change in volume per unit volume of the body is called the '**volume strain'** and the normal force acting per unit area of the surface (pressure) is called the normal stress or **volume stress**. For small strains, the ratio of the volume stress to the volume strain is called the '**Bulk modulus' of the material of the body**. It is denoted by K. Then $K = \frac{-P}{\delta V / V}$

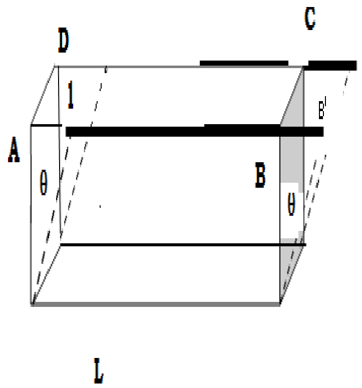
Negative sign in formula implies that when the pressure increases volume decreases and vice-versa. The reciprocal of the Bulk modulus of the material of a body is called the "**compressibility**' of that material. Thus, compressibility = 1/K

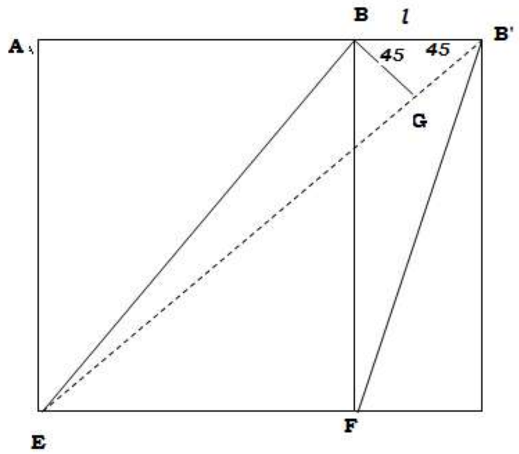
Poisson's ratio (σ)

When a material is stretched, the increase in its length (Linear strain α) is accompanied by decrease in cross section (lateral strain β). Within the elastic limit, the lateral strain is proportional to longitudinal strain and the ratio between them is a constant for a material known as **Poisson ratio (**σ). σ = lateral strain / longitudinal strain, i.e, $\sigma = \frac{\beta}{\alpha}$

The ratio of change in diameter/breadth to original diameter/breadth is called the **lateral strain (β)**. The ratio of change in length to original length is called the **linear strain (α)**.

Relation between Rigidity Modulus (n), linear strain (α) &Young's modulus (Y) :





Let the face ABCD of a cube of side L be sheared by a Force F through an angle θ.

Then the Shearing stress, $T = \frac{F}{L^2}$

Shearing Strain, $\theta = \frac{l}{L}$

Therefore Rigidity Modulus (n) = $\frac{T}{\theta}$

Shearing stress along AB is equivalent to expansive stress along EB and compressive stress along AF. Let α be the longitudinal expansive strain per unit Stress per unit length and β be the lateral compressive strain per unit stress per unit length respectively.

Elongation along EB= $EB.\alpha.T.$

Compression along AF = $EB..T.\beta$ (Since AF =EB)

Net extension of the body is GB^1= $EB..T(\alpha+\beta)) = L.\sqrt{2}.T(\alpha+\beta))$ ---- (1)

From the Triangle AEB, $(EB)^2 = (AB)^2 + (BE)^2$

$(EB)^2 = L^2 + L^2 \rightarrow$ $\mathbf{EB = L.\sqrt{2}}$

Also , from right angled triangle BB^1G,

Elongation $GB^1 = BB^1 \cos 45$ (θ is approximately 45 in the Δle B B^1G) $\rightarrow$ $\mathbf{GB^1 =} \dfrac{l}{\sqrt{2}}$

Eqn (1) becomes, $L.\sqrt{2}.T(\alpha+\beta)) = \dfrac{l}{\sqrt{2}}$

$$\frac{T}{\left(\frac{l}{L}\right)} = \frac{1}{2(\alpha+\beta)}$$

$$\boxed{n = \frac{1}{2(\alpha+\beta)}}$$

If the unit stress (F/A equal to 1) acting on a body along longitudinal direction, the strain produced is linear strain (α). Then the Young's modulus, Y = stress/strain,

$\boxed{\mathbf{Y} = \frac{1}{\alpha}.}$ This is the relation between young's modulus (Y) and linear strain (α).

$$n = \frac{1}{2\alpha\left(1+\frac{\beta}{\alpha}\right)} = \frac{1}{2\alpha(1+\sigma)} = \frac{Y}{2(1+\sigma)} \Rightarrow \boxed{Y = 2n(1+\sigma)}$$

LIMITS OF σ : Generally the Poissions ratio of materials varies from -1 to 0.5

We have the Equation $3K(1-2\sigma) = 2n(1+\sigma)$

1. If σ be a positive quantity, $(1-2\sigma)$ should be positive
   $2\sigma<1 \quad = \sigma < 0.5$,

A perfect incompressible material deformed elastically at small strains would have a poissions ratio exactly 0.5.

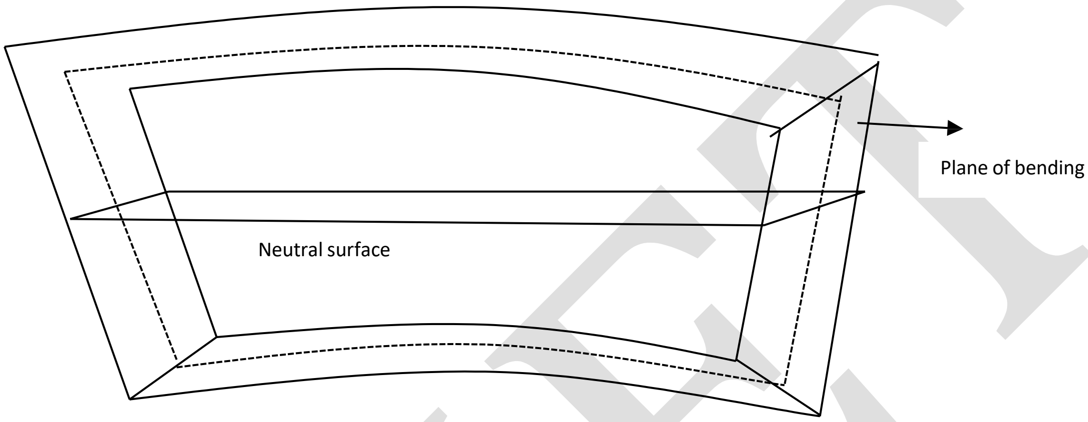
2. If σ be a negative quantity, $(1 + \sigma)$ should be positive, $\sigma < -1$.

Resilience: Capacity to resist a heavy stress without acquiring permanent elongation.

BENDING OF BEAM

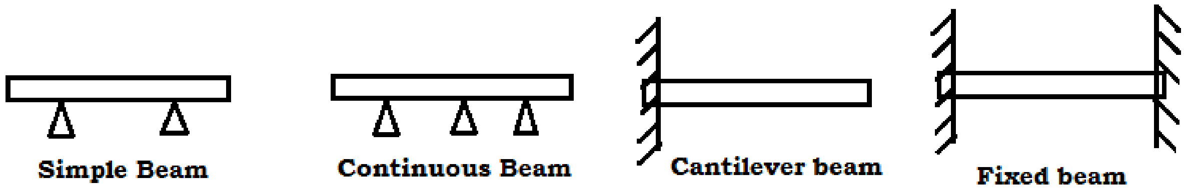
Beam is a bar or rod of uniform cross section whose length is very much larger than thickness. When such a beam is fixed at one end and loaded at the other, the beam is bent under the action of couple produced by the load. Upper surface of the beam gets stretched and lower surface gets compressed. The extension is maximum in the upper most filaments and compression, maximum in the lowermost ones. The surface which does not get affected is known as neutral surface.

If the bending is uniform, the longitudinal filaments get bent into circular arcs in planes parallel to the plane of symmetry (plane of bending).The line of intersection of plane of bending with neutral surface is called neutral axis.



Types of Beam:

Depending on the support, beams are classified as following four types



1. **Simple beam**: It is bar resting upon supports at its ends and is the kind most commonly in use.
2. **Continuous beam**: It is a bar resting upon more than two supports.
3. **Cantilever beam**: It is a beam whose one end is fixed and the other end is free.
4. **Fixed beam**: A beam fixed at its both ends is called a fixed beam.

Applications of beam: Beams are used

i) In the fabrication of trolley ways.

ii) In the Chassis/ frame as truck beds.

iii) In the elevators.

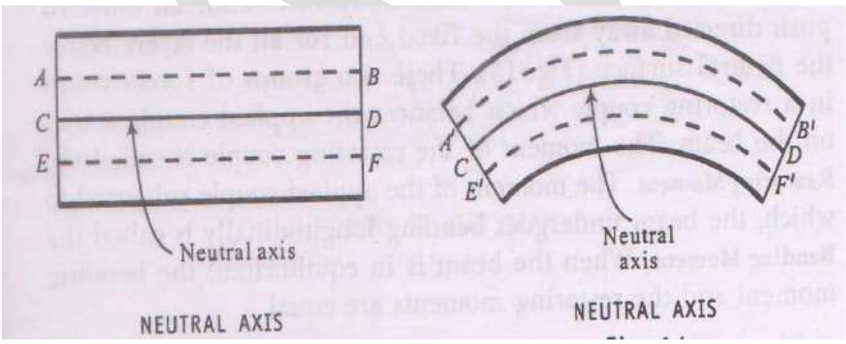
iv) In the construction of flatform and bridges.

v) Beams are an integral part of Civil engineering structural elements (bridges, dams, multistoreid buildings).

vi) In the measuring devices (Tunneling microscopes)

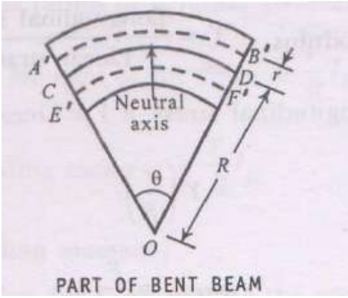
BENDING MOMENT The load is attached to the beam at the other end the beam bends. The successive layers now strained.

In the figure, ABCD is a beam fixed at AD and loaded at the end B. EF is neutral axis. The applied load (W) tends to bend the beam, an equal and opposite reactional force W^1 will be acting upwards along pp^1. These two forces constitute a couple and the moment of this couple is called **bending moment**. When the beam is in equilibrium position the bending moment and restoring moment should be equal. In order to find the expression for moment of restoring couple, consider a fiber A'B' at a distance r from neutral axis CD shown in Fig. Let the beam be bent in the form of circular arc subtending angle θ at the centre of curvature O.



Consider a long uniform beam whose one end is fixed. The beam can be thought of made up of a number of parallel layers like AB, CD, EF etc. If now a load is attached to the other end the beam bends. The successive layers now strained. The layer AB which is above the neutral axis will be elongated to A'B' and the one like EF below the neutral surface will be contracted to E'F'. CD is the neutral surface which does not change.

The shape of the different layers of the bent beam can be imagined to form part of concentric circles of varying radii as shown in figure

.

Let R be the radius of curvature of the circle to which the neutral surface forms a part.

$$CD = R\theta$$

where θ is the angle subtended by the layers at the centre of curvature O.

Then, the length of fibre in the unstrained position AB= CD = Rθ

The length of fibre in the strained position A'B' = (R + r)θ

Change in length = (R + r)θ -Rθ = rθ

Original length = Rθ

Liner strain $= \frac{r\theta}{R\theta} = \frac{r}{R}$

Youngs modulus Y=$\frac{Longitudinal\ stress}{Linear\ strain}$

Longitudinal stress=Y x Linear strain

$=Y\frac{r}{R}$

Stress $=\frac{F}{a}$ where F is is the force acting on the beam and a is the area of the layer AB

$\frac{F}{a} = Y\frac{r}{R}$

$F = \frac{Yar}{R}$

Moment of this force about the neutral axis

=F x its distance from the neutral axis.

$$M = F \times r = \frac{Yar^2}{R}$$

Total moment of forces acting on the entire beam $M = \sum \frac{Yar^2}{R} = \frac{Y}{R}\sum ar^2 = \frac{Y}{R} I$, here I = $\sum ar^2$ = aK^2 & I is Geometrical Moment of Inertia.

Bending moment of the beam, $\boxed{\mathbf{M} = \frac{Y}{R} I}$

For rectangular cross section, area = b X d, $k^2 = \frac{d^2}{12}$

$$I = ak^2 = \frac{bd^3}{12}$$

$$M = \frac{Ybd^3}{12R}$$

For Circular cross section, area = πr^2, $k^2 = \frac{r^2}{4}$

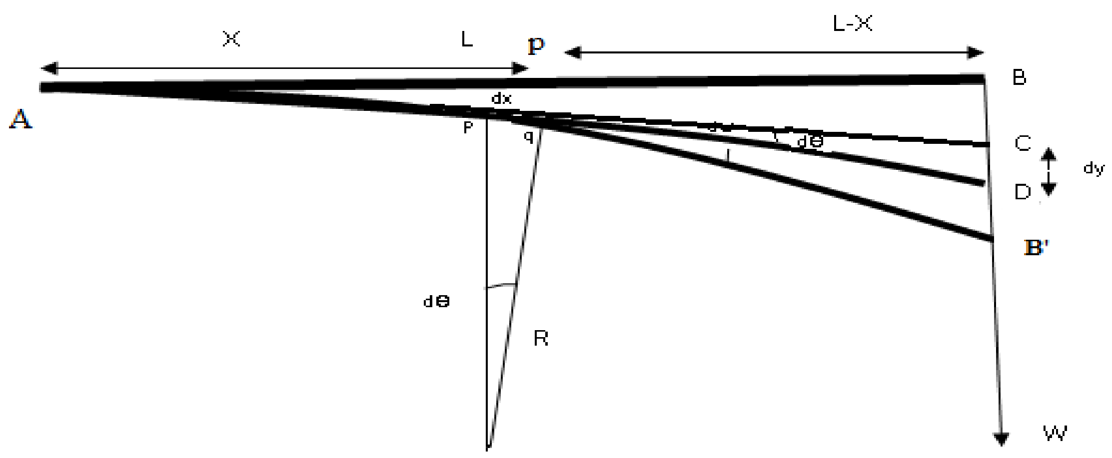
$$I = ak^2 = \frac{\pi r^4}{4}$$

$$M = \frac{Y\pi r^4}{4R}$$

Where I is the geometrical moment of inertia and k is **Radius of gyration**, It is the distance of a point from the axis of rotation where whole mass of the body is assumed to be concentrated.

CANTILEVER

A beam fixed horizontally at one end and loaded at the other is called **Cantilever**.



Let AB be the neutral axis of the cantilever of length L fixed at A and loaded at B. Consider a section P of the beam at a distance x from A.

Bending moment = W (L-X) $= Y\frac{I}{R}$

$$\text{i.e, } W(L-X) = Y\frac{I}{R} \text{ ----------------------} \quad (1)$$

Here R is the radius of curvature of neutral axis at P. The radius of curvature is different at different points . For a point Q at a small distance dx from P, it is same as at P.

Therefore PQ = dx = R.dΘ $\Rightarrow$ R = (dx /dθ) --------- (2)

Bending moment W (L-X) = $Y\frac{Id\theta}{dx}$ [substituting (2) in (1)]

$$d\theta = \frac{W(L-X)dx}{YI} \text{ -------------} \quad (3)$$

Draw tangents to the neutral axis at P and Q meeting the vertical line at C and D. The angle subtended by them is dΘ. The depression of Q below P is given by

$$dy = (L-X)d\theta \quad \text{----} \quad (4)$$

Substituing Eqn.(3) in Eqn.(4) Then, dy $= W\frac{(L-X)^2}{YI}.dx$

Total depression BB^1 of the loaded end $\int dy = \int_0^L W\frac{(L-X)^2}{YI}.dx$

$$\int dy = \int_0^L W\frac{(L^2-2LX+X^2)}{YI}.dx$$

$$= W\frac{[L^2X - LxX^2 + \frac{X^3}{3}]}{YI}$$

$$\boxed{\mathbf{y} = W\frac{L^3}{3YI}}$$

For rectangular cross section I $= \frac{bd^3}{12}$ Then the depression, y $= \frac{4mgl^3}{Ybd^3}$ [W = mg]

Therefore Young's Modulus Y $= \frac{4mgl^3}{ybd^3}$

Failures of engineering materials - ductile fracture, brittle fracture, stress concentration, fatigue and factors affecting fatigue (only qualitative explanation),

Failures (Fracture/Fatigue)

Mechanical failure is defined as any change in the size, shape or material properties of a structure, machine or machine parts that renders it incapable of satisfactory performance its intended function.

A Machine is meant for repeated use. Machine has many structural components/parts [example parts of aircraft, automobile, pumps etc] that are subjected to repeated loading while in use it gets stressed. Due to their continuous use, they are stressed repeatedly and cracks begin to form. Formation of a crack which results in a complete destruction of continuity constitutes fracture.

Types of Failure :

1. Simple fracture

a) Ductile fracture

b) Brittle fracture

2. Fatigue Failure

3. Creep fracture

1. Simple Fracture : Simple fracture is the separation of a body into two or more pieces in response to an imposed stress that is static (i.e., constant or slowly changing with time) and at temperature that are low relative to melting temperartureof the material. The applied stress may be tensile, compressive, shear, or torsional. For engineering materials, two fracture modes are possible: ductile and brittle based on the ability of the material to deform plastically.

Any fracture process involves two steps :-

a. crack formation and

b. crack propagation

The mode of fracture is highly dependent on the mechanism of crack propagation.

Brittle fracture :

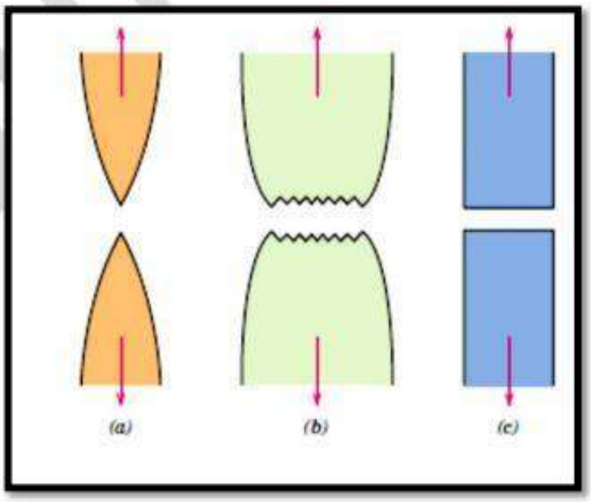
- In brittle fracture, cracks may spread extremely rapidly, with very little accompanying plastic deformation.
- The cracks may be said to be unstable, and crack propagation , once started, will continue spontaneously without an increase in magnitude of the applied stress.
- In brittle materials little or no plastic deformation with low energy absorption before fracture.

Ductile Fracture :

- Ductile materials typically exhibit substantial plastic deformation with high energy absorption before fracture.
- The presence of plastic deformation gives warning that fracture is imminent, allowing preventive measures to be taken.
- More strain energy is required to induce ductile fracture in as much as ductile materials are generally tougher.
- Under the action of an applied tensile stress, most metal alloys are ductile, whereas ceramics are notably brittle, and polymers may exhibit both types of fracture.

Ductile fracture surfaces will have their own distinctive features on both macroscopic and microscopic levels.

Figure (3.1) shows schematic representations for two characteristic macroscopic fracture profiles.

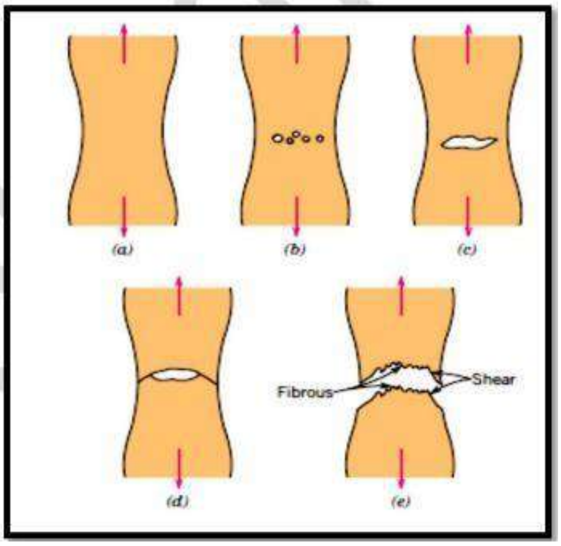


Figure(3.1)

(a) Highly ductile fracture in which the specimen necks down to a point.

(b) Moderately ductile fracture after some necking.

(c) Brittle fracture without any plastic deformation.



Figure(3.2): Stages in the cup-andcone fracture.

(a) Initial necking.

(b) Small cavity formation.

(c) Coalescence of cavities to form a crack.

(d) Crack propagation.

(e) Final shear fracture at a °45 angle relative to the tensile direction.

(a) First, after necking begins, small cavities, or micro voids, form in the interior of the cross section

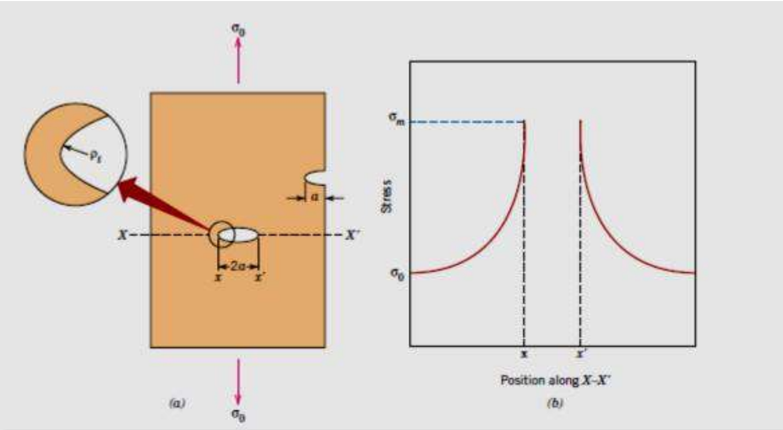
(b) Next, as deformation continues, these micro voids enlarge, come together, and coalesce to form an elliptical crack, which has its long axis perpendicular to the stress direction.

(c) The crack continues to grow in a direction parallel to its major axis by this micro void coalescence process.

(d) Finally, fracture ensues by the rapid propagation of a crack around the outer perimeter of the neck by shear deformation at an angle of about °45 with the tensile axis

Sometimes a fracture having this characteristic surface contour is termed a cup-and-cone fracture because one of the mating surfaces is in the form of a cup, the other like a cone.

Stress Concentration The measured fracture strengths for most brittle materials are significantly lower than those predicted by theoretical calculations based on atomic bonding energies. This discrepancy is explained by the presence of very small, microscopic flaws or cracks that always exist under normal conditions at the surface and within the interior of a body of material. These flaws are a detriment to the fracture strength because an applied stress may be amplified or concentrated at the tip, the magnitude of this amplification depending on crack orientation and geometry. This phenomenon is demonstrated in Figure 3.6, a stress profile across a cross section containing an internal crack. As indicated by this profile, the magnitude of this localized stress diminishes with distance away from the crack tip. At positions far removed, the stress is just the nominal stress or the applied load divided by the specimen cross-sectional area (perpendicular to this load). Due to their ability to amplify an applied stress in their locale, these flaws are sometimes called stress raisers.



Figure(3.6) : (a) The geometry of surface and internal cracks. (b) Schematic stress profile along the line X–X in (a), demonstrating stress amplification at crack tip positions.

If it is assumed that a crack is similar to an elliptical hole through a plate, and is oriented perpendicular to the applied stress, the maximum stress, occurs at the crack tip and may be approximated by

$$\sigma_m = 2\sigma_0\left(\frac{a}{\rho_t}\right)^{1/2}$$

where : σ_0 is the magnitude of the nominal applied tensile stress, ρ_t : is the radius of curvature of the crack tip (Figure 3.6a), and a : represents the length of a surface crack, or half of the length of an internal crack. Sometimes the ratio is denoted as the stress concentration factor (K_t) which is simply a measure of the degree to which an external stress is amplified at the tip of a crack.

Sometimes the ratio is denoted as the stress concentration factor (Kt) which is simply a measure of the degree to which an external stress is amplified at the tip of a crack.

$$K_t = \frac{\sigma_m}{\sigma_0} = 2\left(\frac{a}{\rho_t}\right)^{1/2}$$

Fatigue Failure : Fatigue is a form of failure that occurs in structures subjected to dynamic and fluctuating stresses (e.g., bridges, aircraft, and machine components). Under these circumstances it is possible for failure to occur at a stress level considerably lower than the tensile or yield strength for a static load. The term ―fatigue‖ is used because this type of failure normally occurs after a lengthy period of repeated stress or strain cycling. Fatigue is important inasmuch as it is the single largest cause of failure in metals, estimated to comprise approximately 90% of all metallic failures; polymers and ceramics (except for glasses) are also susceptible to this type of failure. Furthermore, fatigue is catastrophic and insidious, occurring very suddenly and without warning. Fatigue failure is brittle like in nature even in normally ductile metals, in that there is very little, if any, gross plastic deformation associated with failure. The process occurs by the initiation and propagation of cracks, and ordinarily the fracture surface is perpendicular to the direction of an applied tensile stress.

FACTORS THAT AFFECT FATIGUE LIFE

The fatigue behavior of engineering materials is highly sensitive to a number of variables. Some of these factors include mean stress level, geometrical design, surface effects, and metallurgical variables, as well as the environment.

Mean Stress

The dependence of fatigue life on stress amplitude is represented on the S– N plot. Such data are taken for a constant mean stress σ_m, often for the reversed cycle situation ($\sigma_m = 0$). Mean stress, however, will also affect fatigue life; this influence may be represented by a series of S–N curves, each measured at a different as depicted schematically in Figure 3.16 As may be noted, increasing the mean stress level leads to a decrease in fatigue life.

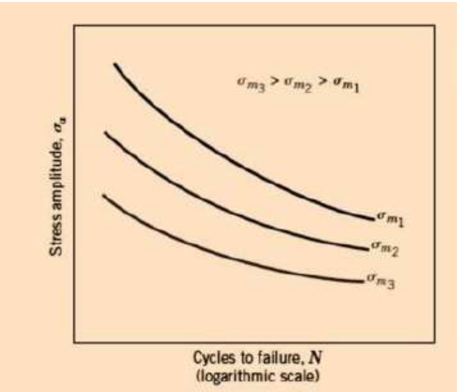
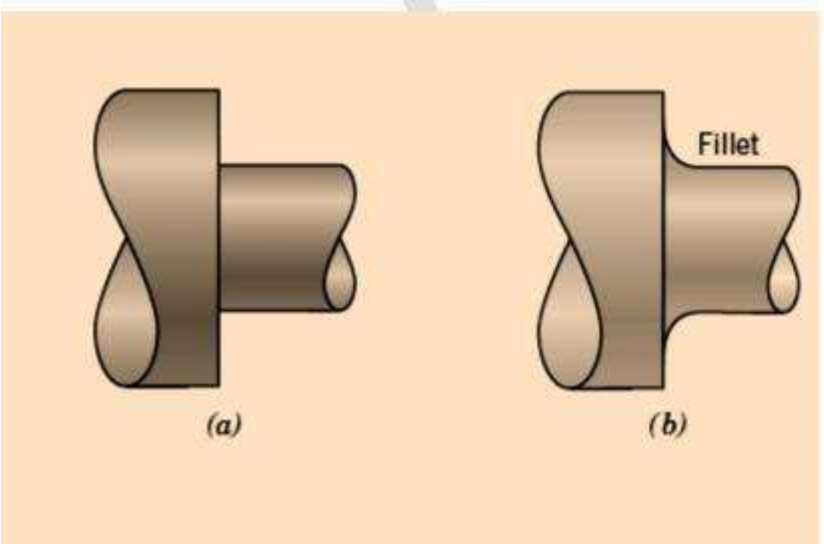


Figure 3.16: Demonstration of the influence of mean stress on S–N fatigue behavior.

Surface Effects: For many common loading situations, the maximum stress within a component or structure occurs at its surface. Consequently, most cracks leading to fatigue failure originate at surface positions, specifically at stress amplification sites. Therefore, it has been observed that fatigue life is especially sensitive to the condition and configuration of the component surface. Numerous factors influence fatigue resistance, the proper management of which will lead to an improvement in fatigue life. These include design criteria as well as various surface treatments

Design Factors The design of a component can have a significant influence on its fatigue characteristics. Any notch or geometrical discontinuity can act as a stress raiser and fatigue crack initiation site; these design features include grooves, holes, keyways, threads, and so on. The sharper the discontinuity (i.e., the smaller the radius of curvature), the more severe the stress concentration. The probability of fatigue failure may be reduced by avoiding (when possible) these structural irregularities, or by making design modifications whereby sudden contour changes leading to sharp corners are eliminated—for example, calling for rounded fillets with large radii of curvature at the point where there is a change in diameter for a rotating shaft (Figure 3.17).



Figure(3.17): Demonstration of how design can reduce stress amplification. (a) Poor design: sharp corner. (b) Good design: fatigue lifetime improved by incorporating rounded fillet into a rotating shaft at the point where there is a change in diameter

Surface Treatments During machining operations, small scratches and grooves are invariably introduced into the work piece surface by cutting tool action. These surface markings can limit the fatigue life. It has been observed that improving the surface finish by polishing will enhance fatigue life significantly.

Case hardening: is a technique by which both surface hardness and fatigue life are enhanced for steel alloys. This is accomplished by a carburizing or nitriding process whereby a component is exposed to a carbonaceous or nitrogenous atmosphere at an elevated temperature. A carbon- or nitrogen-rich outer surface layer (or ―case‖) is introduced by atomic diffusion from the gaseous phase. The case is normally on the order of 1 mm deep and is harder than the inner core of material.

ENVIRONMENTAL EFFECTS Environmental factors may also affect the fatigue behaviour of materials. A few brief comments will be given relative to two types of environment assisted fatigue failure: thermal fatigue and corrosion fatigue

Thermal fatigue : is normally induced at elevated temperatures by fluctuating thermal stresses; mechanical stresses from an external source need not be present

Corrosion Fatigue : Failure that occurs by the simultaneous action of a cyclic stress and chemical attack is termed corrosion fatigue. Corrosive environments have a deleterious influence and produce shorter fatigue lives. Even the normal ambient atmosphere will affect the fatigue behavior of some materials.

Questions

1. Define elasticity.

2. Write a note on strain hardening and strain softening.

3. Explain stress – strain curve with Hooke's law.

4.. Derive an expression for bending moment in terms of moment of inertia.

5. Derive the expression for bending moment and depression at a loaded end of single cantilever.

6. Derive the expression of rigidity modulus (n) in terms of linear strain (α) and Youngs modulus(Y).

7. Explain different types of beams and its engineering applications.

8. A force of 10 N is applied along the length of a wire of length 4m and radius 0.03 x 10^{-2} m. Calculate the extension produced in the wire. Given the Young's modulus of the material of the wire Y is 2.1 x 10^{11} N/m^2.

9. Calculate the force required to produce an extension of 1mm in a steel wire of length 2meter and diameter 1 mm. Given, Young's modulus of the material of the wire Y is 2.1 x 10^{11} N/m^2.

10. A metal cube of side 0.20 m is subjected to a shearing force of 4000 N. The top surface is displaced through 0.50 cm with respect to the bottom. Calculate the shear modulus of elasticity of the metal.

.

MODULE 3

ACOUSTICS, RADIOMETRY and PHOTOMETRY

The branch of physics which deals with generation, reception, propagation and analysis of sound is called acoustics.

The acoustical properties of a room or hall have considerable effect on the clarity and intelligibility of speech or music produced in the hall. Thus, the study of sound waves plays an important role in many engineering and non - engineering applications.

Types of Acoustics

The areas of acoustical studies and their applications include:

Architectural acoustics - Study of sound waves in closed halls and buildings.

Musical acoustics - Physics of musical instruments.

Engineering acoustics - Technology of sound production and recording, study of vibrations of solids and their control (including noise control).

Bio-acoustics / Medical acoustics - Use of sound in medical diagnosis and therapy.

Basic Terminologies

The different musical sounds are distinguished from each other by the following characteristics:

(i) Pitch (or) frequency

Pitch is the characteristic of a sound which distinguishes between a shrill sound and a grave sound.

The pitch of a musical note is the sensation conveyed to our brain by the sound waves falling on our ears.

Pitch depends directly on the frequency of the sound waves. Pitch is measured in Hertz (Hz).

Example

- The voice of women and children has high pitch because the frequency of sound is high.
- The voice of an old man has low pitch because the frequency of sound is low.
- In guitars, thicker wires give a lower frequency and thinner wires give a length frequency.

(ii) Quality (or) Timbre

Quality or timbre of the sound wave is a characteristic which enables us to distinguish between musical notes emitted by different instruments or voices even though they have the same pitch and loudness.

(iii) Intensity of sound (I)

Intensity of a sound wave (I) at a point is defined as the amount of sound energy Q flowing per second per unit area held normally at the point to the direction of the propagation of sound wave.

Intensity of sound wave $I = \frac{Q}{tA}$ where Q - Amount of sound energy flowing, t - Time of flow, and A - Area normal to the propagation of sound.

Intensity, $I = \frac{P}{A}$ where Power, $P = \frac{Q}{t}$

Intensity is a measurable physical quantity. It is expressed in joule second^{--1} metre^{--2} or watt metre^{-2} (Wm^{-2}).

(iv) Sound intensity level or relative intensity of sound

- The logarithmic ratio of intensity of a sound to standard intensity ($I_o = 10^{-12}\ Wm^{-2}$) is known as sound intensity level or relative intensity of sound.
- Standard intensity of sound is the minimum audible sound intensity heard by our ears.
- Sound intensity level, $\beta = \log_{10}\left(\frac{I}{I_0}\right)$ bel
- The unit for sound intensity level is bel named in honour of Alexander Graham Bell,

Note: Consider sound intensity, $I = 10I_o$

Then Sound intensity level is $\beta = \log_{10}\left(\frac{10I_o}{I_0}\right)$ bel

Then we get $\boldsymbol{\beta = \log_{10} 10 = 1\text{bel}}$

Similarly, if $I = 100I_o$

Then Sound intensity level is $\beta = \log_{10}\left(\frac{100I_o}{I_0}\right)$ bel

Then we get $\boldsymbol{\beta = \log_{10} 100 = 2\text{bel}}$

- Bel is the sound intensity level of a sound whose intensity is ten times the standard intensity.
- In practice, bel is a larger unit. Hence, another unit known as decibel (dB) is more often used.

1bel=10 decibel

- Hence, sound intensity level is measured in decibel is $\boldsymbol{\beta} = 10\ \mathbf{log_{10}}\ (\frac{I}{\mathbf{I_0}})\ \mathbf{dB}$

Reflection and Refraction of Sound Waves

Reflection and refraction are two important phenomena that occur with sound waves as they travel through different mediums.

Reflection of sound waves: Reflection occurs when sound waves encounter a boundary between two different mediums and bounce back. The angle of incidence (the angle at which the sound wave strikes the boundary) is equal to the angle of reflection (the angle at which the sound wave bounces off the boundary).

The reflection of sound wave produces echoes and reverberation.

Refraction of Sound Waves: Refraction takes place when sound waves travel through mediums with varying densities, causing the waves to change direction. The change in direction is due to the difference in the speed of sound in the two mediums. When a sound wave passes through a medium where the speed of sound is different, one side of the wave front moves faster than the other, causing the wave to bend.

Reverberant sound (Reverberation): The existence or prolongation or persistence of sound in a room (due to multiple reflections from surfaces) even after the source of sound has stopped to emit the sound is called reverberant sound or reverberation.

Reverberation time: The time duration upto which a sound persists even after the source of sound has stopped to emit the sound is called reverberation time. It is measured as the time taken by the sound to fall below the minimum audibility after source of sound has stopped to emit the sound.

Importance of Reverberation Time

a) Noise Effect:

- Any unpleasant sound to our ears is called noise.

- Noise causes irritation and strain to our ear. Noise of high intensity may cause permanent or temporary deafness.
- Noise can be caused by various sources, such as machinery, traffic, ventilation systems, or other environmental factors.
- High reverberation time can lead to the creation of noise.

b) Dead Effect:

- The dead effect in the room is due to an extremely short reverberation time, typically less than 0.1 seconds.
- The dead effect, also known as a "dead room" or "anechoic chamber," is the opposite of a reverberant room.
- In a dead room, the surfaces are designed to absorb sound energy entirely rather than reflect it.
- Dead rooms are used for various purposes, such as audio testing and measurements, to eliminate reflections and achieve accurate and controlled acoustic condition.

Optimum Reverberation Time Values for Good Auditoriums

For a good auditorium, the reverberation time generally falls within the following ranges:

1. **Concert Halls:** Reverberation time of approximately 1.8 to 2.2 seconds is considered ideal for classical music performances. This allows the sound to blend and enrich the musical experience.

2. **Opera Houses:** Reverberation time of around 1.6 to 1.9 seconds is often preferred for opera performances. A slightly shorter reverberation time helps maintain clarity in vocal performances.

3. **Theaters**: Theater spaces can have a slightly shorter reverberation time, typically between 1.2 to 1.6 seconds. This allows for good speech intelligibility and helps the audience hear the dialogue clearly.

4. **Multi-purpose Halls:** These venues may have adjustable acoustics to accommodate various events. Reverberation time can vary from 1.2 to 2.0 seconds depending on the configuration.

Absorption of Sound

- When a sound wave strikes a surface there are three possibilities:

(a) Part of energy is absorbed

(b) Part of it is transmitted

(c) Remaining energy is reflected

- The property of the surface to convert sound energy into other forms of energy is known as absorption.
- The effectiveness of surface in absorbing sound energy is expressed by absorption coefficient denoted by α (alpha).

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

Open Window Concept

- An open window allows sound incident on it to completely pass through without any reflection and hence behaves as a perfect absorber of sound.
- An unit area of an open window is taken as the standard unit of absorption.
- Absorption coefficient is defined as the reciprocal of the area of the sound absorbing surface that absorbs the same quantity of sound as that of a 1 m^2 of an open window.

  Ex: If 5 m^2 of a material absorbs the same quantity of sound as 1 m^2 of an open window, then the absorption coefficient of the material is 1/5 = 0.2.
- The unit of absorption coefficient is sabin or open window unit (O. W. U.).

Average Value of Absorption Coefficient

- Let the α_1 , α_2 , α_3 , …. , α_n be the absorption coefficients of the different materials in a hall whose surfaces exposed to sound are S_1 , S_2 , S_3 , …. S_n respectively, measured in m^2.
- The total absorption is given by, A = $\alpha_1 S_1 + \alpha_2 S_2 + \alpha_3 S_2 + - - + \alpha_n S_n = \sum_{i=1}^{n} \alpha_i S_i$
- The average value of absorption co − efficient, $\bar{\alpha} = \frac{\alpha_1 S_1 + \alpha_2 S_2 + \alpha_3 S_2 + - - - + \alpha_n S_n}{S_1 + S_2 + S_3 + - - - + S_n} = \frac{\sum_{i=1}^{n} \alpha_i S_i}{\sum_{i=1}^{n} S_i}$
- The value of absorption coefficient varies between 0 and 1.

Absorptive power

The absorptive power of a surface is defined as the ratio of sound energy absorbed over a certain time to the radiant sound energy incident on it at the same time.

Requisites for Acoustics in Auditoriums

1. The sound heard must be sufficiently loud in every part of the hall and no echoes should be present.
2. The total quality of speech and music must remain unchanged.
3. The reverberation time must neither be too large or too small.
4. There should be no concentration of sound in any part of the hall.
5. There should be no extraneous noise.
6. There should be no Echelon effect.
7. There should be no resonance within the auditorium.

Factors Affecting the Acoustics and their Remedial Measures

1. **Reverberation time**

If reverberation time in a hall is too large, there is an overlapping of successive sounds which results in a loss of clarity and echo. On the other hand, if reverberation time is very small, loudness is not sufficient. The speaker may find no response from the audience. Such a hall is considered as dead by the speaker. Thus, it is very important that reverberation time in a hall should not be too long or short. A satisfactory or preferred value of the reverberation time is called optimum reverberation time.

Optimum reverberation time is obtained by the following ways:

- Providing many windows and ventilators.
- Covering a part of the ceiling, walls and even the back of chairs with suitable sound absorbing materials like felt, fibre board, glass, wool etc.
- Using curtains with folds.
- Covering the floor with carpets and having graded ceiling tops.
- Having a good-size of audience.
- Decorating the walls with pictures and maps.

2. Loudness

- Loudness is the degree of sensation produced in the ear.
- If the intensity of sound is weak, loudness may go below the level of audibility.
- Sufficient loudness in every part of the hall is important for satisfactory hearing.

The loudness of sound is increased by the following ways:

- To achieve good loudness, maximum reflection of sound from the stage is desirable so that there is no loss of sound energy. This can be done by using a large sounding board behind the speaker.
- Large polished wooden reflecting surfaces above the speakers are helpful.
- Use of good quality loudspeakers is essential.
- Low ceilings are helpful for better reflection of sound.

3. Focusing

Sound waves that reflect from the concave surfaces of a building get focused to a point. The intensity of sound will be maximum at such points and zero at other places. This is called focusing effect.

Uniform distribution of sound in a hall can be achieved in the following ways:

- There should not be any curved surfaces in the hall. If such surfaces are present, they should be covered with suitable sound absorbing materials.
- Ceiling should be as low as possible.

4. Echoes

- When a sound wave falls on a reflecting surface (more than 17 meter away), it is reflected as a distinct repetition of direct sound. This reflected sound is called an echo.
- Echoes occur due to the reflected sound waves. They reach the listener a little later than the direct sound, which causes confusion. This defect is common particularly when the reflecting surface is curved.

Remedies to reduce echoes are:

- Providing low ceiling.
- Covering walls and ceiling with suitable sound absorbing materials.

5. Echelon effect

Sound produced in front of regular structures like a set of railing or staircase or any regular spacing of reflecting surfaces may produce sound notes due to regular repetition of echoes of the original sound. This effect is called as Echelon effect.

Remedies to reduce the echelon effect are:

- Regular structure like a stair case or a set of railings in the hall should be avoided.
- The stair cases may be covered with carpets to avoid reflection.

6. Resonance

- If the frequencies of the original sound and that of the newly created sound are the same, it may result in resonance. Such vibrations are called ***resonant vibrations.***
- Due to the interference between original sound and the newly created sound, the original sound is distorted. Hence, it leads to an unpleasant effect. Such resonant vibrations should be suitably damped.
- Resonance effect can be rectified by hanging large number of curtains in the hall.

7. Noise

Unpleasant sound which creates harsh or jarring effect to the human ear is called noise.

There are three types of noises.

(i) Inside noise, (ii) Air - borne noise, and (iii) Structure - borne noise

(i) Inside noise

Noise produced inside the room is known as inside noise.

Examples:

- The sound created by the movement of people, crying babies, movement of furniture.
- The sound produced from machines, typewriters, etc.

Remedies to reduce inside noise:

- Machines and typewriters can be placed over sound absorbing materials.
- The walls, floors and ceilings can be covered with suitable sound absorbing materials

- The engines that create noise may be fitted on the floor with a layer of wood or felt between them.

(ii) Air-borne noise

Noises coming through open windows, doors and ventilators are known as air-borne noises and are common in a densely populated area.

Remedies to reduce inside noise:

- Using double doors and windows with separate frames and placing sound absorbing material in between them.
- By allotting proper places for doors and windows.
- Using heavy glasses in doors, windows and ventilators.
- By making the hall air-conditioned.

(iii) Structure-borne noise

Noises conveyed through the structures of a building are called structure-borne noises.

Examples:

The operation of machinery, movement of furniture, footsteps etc. produce structural vibrations giving rise to structure-borne noise.

Remedies to reduce structure-borne noises:

- Noises from water pipe can be controlled by using rubber couplings at junctions.
- Using double walls with an air space between them.
- Covering the floors and ceilings with suitable sound absorbing materials and anti-vibration mounts.

Concept of Noise

- Noises are generally measured by sound pressure level (SPL).
- The reference intensity for the threshold of hearing of sound pressure is $2\text{x}10^{-5}$ Nm^{-2} or sound intensity of 10^{-12} Wm^{-2}.

- The level of sound pressure P is said to be L_p decibels greater than a reference sound pressure P_o according to the following definition:

$$\text{Sound Pressure Level } (L_p \text{ or SPL}) = 10 \log_{10}\left(\frac{P^2}{P_o^2}\right) \text{ dB}$$

Sound Measurement (Intensities, Pressures and Decibels) in Air at Room Temperature and Sea Level Pressure

Intensity (W/m^2)	Pressure (Nm^2)	dB	Sound source
100	2,00,000	200	Rocket take off
1.0	20	120	Boiler shop
10^{-2}	2.0	100	Siren at 5 meters
10^{-4}	0.2	80	Heavy machinery
10^{-6}	0.02	60	Normal conversation at 1 meter
10^{-8}	0.002	40	Public library
10^{-12}	2×10^{-5}	0	Threshold of hearing

Noise Meters

- Noise meters are the instruments specially designed for noise measurement from low to high frequencies that are within the human ear capacity.
- Noise meters use dB scales for routine measurement of general noise levels.
- Refined noise meters have been developed to take care of peak noise levels, duration of noise exposure, and quality of noise which are aspects of a specified noise situation.
- The commonly used noise meters are Sound Level Meter (SLM) and Noise Dosimeter.

Impact of Noise

Noise has the following four impact on multistoried buildings:

1. Speech privacy
2. Background noise (e.g fan, a.c, generator, printer)
3. Sound masking
4. Orientation of buildings

1. Speech privacy:

- It is an issue within office building, including individual work space, inside conference halls and between offices.
- It mainly affects the quality of work in the adjacent office.

2. Background noise:

Excessive background noise can adversely affect the work space. At the same time, too little background noise can reduce speech privacy, allowing one to hear not only what's happening in their workspace but also elsewhere.

3. Sound masking:

It blends the noise levels from building systems and exterior sources by utilizing electronic noise systems. Traditional sound masking setup typically involve loudspeakers positioned above the ceiling.

4. Orientation of buildings:

The orientation of a building can significantly affect noise impact, particularly for rooms perpendicular to roadways. This is because:

(a) a noise pattern can be more annoying in perpendicular rooms.

(b) windows on perpendicular walls don't reduce noise as effectively as those on parallel walls because of the angle of sound.

Apartment dwellers are often annoyed by noise in their homes, especially when the building is not well designed.

Sound Insulation

- The art of preventing the transmission of noise inside or outside the hall or rooms of a building is known as sound insulation. It is also called sound proofing
- Sound insulation is used to reduce the level of sound when it passes through the insulating building component.
- The basic principle of sound insulation is to suppress the noise.

Sound Insulation Measurement

- Sound is transmitted through most walls and floors by setting the entire structure into vibration. This vibration generates new sound waves of reduced intensity on the other side. The passage of sound into one room of a building from a source located in another room or outside the building is termed “sound transmission”.

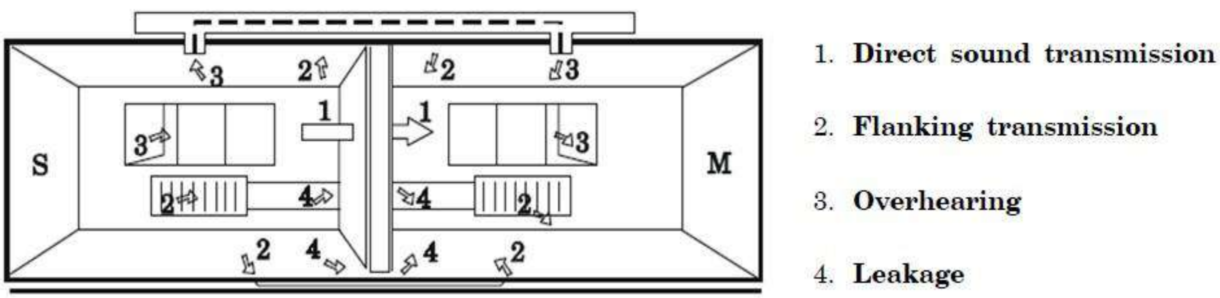


Fig. Sound insulation and its measurement

- The sound reduction index R is used to measure the level of sound insulation provided by a structure such as a wall, window, door, or ventilator. It is expressed in dB.

Methods of Sound Insulation

The method of sound insulation will depend on the type of noise to be treated and the degree of sound insulation required. The methods of sound insulation can thus be classified into three main categories.

1. When source of noise is in the room itself

Following are the methods of sound insulation which are commonly used when the source of noise is situated in the room to be treated for sound insulation:

(i) Improvement in working methods

(a) A working method creating less noise may be adopted. For instance, welding may be preferred to riveting.

(b) The machinery like type writers etc. should be placed on absorbent pads.

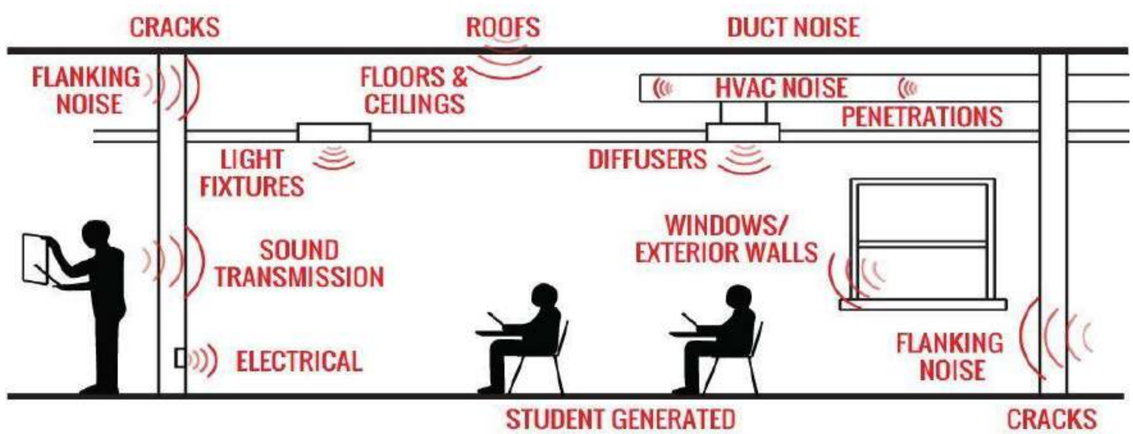
(c) The engine should be fitted on the floor with a layer of wood or felt between them.

(ii) Acoustical treatment

(a) The wall floors and ceilings should be provided with sound absorbing materials.

(b) The sound absorbing materials should be mounted on the surfaces near the source of noise.

(c) The acoustical treatment of the room considerably reduces the noise level in the room.



2. When noise is air-borne

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

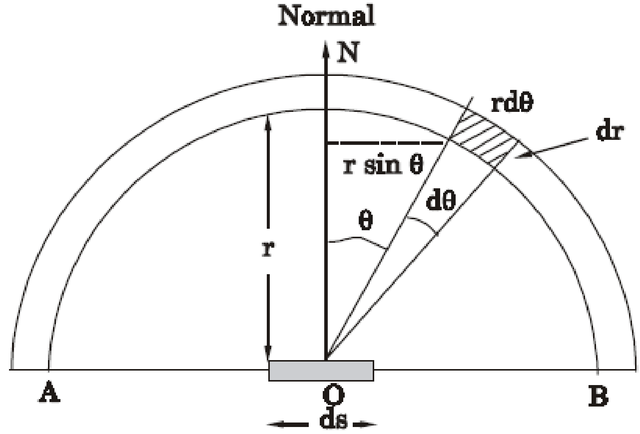
1. By avoiding opening of pipes and ventilators.
2. By allotting proper places for doors and windows.
3. Using double doors and windows with separate frames and having insulating material in them.
4. Using heavy glass in doors, windows and ventilators.
5. By making arrangements for perfectly shutting the doors and windows.

3. When noise is structure-borne

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

1. Treatment of floors and ceilings with suitable sound absorbing material and antivibration mounts.
   (i) By using floating floors and suspended ceilings.
   (ii) Soft floor finish (carpet, cork, vinyl, rubber, etc.)
   (iii) Resilient (anti vibrations) mounts help considerably in reducing structure-borne sound.
2. Using double walls with air space between them.
3. Insulation of machinery.

Expression for Transport of Sound Energy in a Hall



Assuming that the sound energy is uniformly distributed throughout the hall, the expression for transport of sound energy in a hall is given by,

$$E_T = \frac{E\,dS\cos\theta}{4\pi r^2}$$

Where, ds is the small element on a plane wall AB, r is the radius, E is the sound energy and Ɵ is angle between the normal to the area ds and r.

Sabine's Formula:

Prof. W.C. Sabine observed the concept of reverberation time for varieties of conditions like empty room, furnished room, small room, auditorium etc. and concluded the following:

(a) Reverberation time depends upon reflectivity of sound form various surfaces available inside the hall. If the reflection is good, reverberation time of the hall will be longer as sound take more time to die out.

(b) Reverberation time depends upon volume of the hall. i.e. T $\propto$ V

(c) Reverberation time depends upon the absorption coefficient of various surfaces present in the hall. For shorter reverberation, absorption should be more. i.e. T $\propto$ 1/A

Hence, $T \propto \frac{V}{A}$ i.e. $T = K\frac{V}{A}$, where K is a constant of proportionality.

(d) It has been further observed that is all the parameters are taken in SI units then, proportionality constant (K) is found to be 0.161.

Hence, $\mathbf{T = 0.161\frac{V}{A}}$, where Absorption 'A' in the equation represents overall absorption which is given as

$$A = \sum_{i=1}^{n} \alpha_i S_i = \alpha_1 S_1 + \alpha_2 S_2 + \alpha_3 S_2 + - - + \alpha_n S_n$$

(e) As absorption coefficient is found to increase with increase in frequency, reverberation time decreases with frequency.

Sabine's Formula for Reverberation Time

According to Sabine, the standard reverberation time T is the time taken by sound wave to fall to one millionth of its original intensity even after the source of sound is cut-off. If E_m is the sound energy of the source before cut-off and during the standard reverberation time, it reduces to $E_m/10^6$.

Therefore, $E = \frac{E_m}{10^6} = E_m\, 10^{-6}$ ----- (1)

W. K. T. $E = E_m e^{-\alpha t}$ -------- (2)

From eq. 1 and eq. 2 we get,

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

$$\textbf{i.e,}\ 10^{-6} = e^{-\alpha t}$$

$$\text{or, } 10^{6} = e^{\alpha t}$$

For optimum reverberation, t=T

$$\text{Hence, } 10^{6} = e^{\alpha T}$$

Taking $\log_e$ on both sides,

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

$$2.303 \times 6 \times \log_{10} 10 = \alpha T \times \log_e e$$

$$\text{Or } T = \frac{6\times2.303\times1}{\alpha} \text{ ------------- (3)}$$

However, $\alpha = \frac{vA}{4V}$ ------------ (4) where v is the velocity of sound (344 ms^{-1}) and V is the volume of the hall.

Substituting eq. (4) in eq. (3), we get, reverberation time, $T = \frac{6\times2.303\times4\times V}{v\times A} = \frac{6\times2.303\times4\times V}{344\times A}$

$$T = \frac{0.161V}{A} \qquad (5)$$

Eq. 5 is known as Sabine's formula for reverberation time.

Measurement of Absorption Coefficient 'α' using Sabine's Formula

Let T_1 be the reverberation time in an empty room. Then,

$T_1 = \frac{0.161V}{A}$ ----- (1), where $A = \sum_{i=1}^{n} \alpha_i S_i$ represents the total absorption.

Let a certain amount of absorbing material of area S and absorption coefficient α' be placed in the room.

The reverberation time will now be,

$T_2 = \frac{0.161V}{A+\alpha' S}$ ----- (2)

Using eq. 1 and 2 we get,

$$\frac{1}{T_1} - \frac{1}{T_2} = \frac{1}{\frac{0.161V}{A}} - \frac{1}{\frac{0.161V}{A+\alpha^F S}}$$

$$= \frac{A}{0.161\,V} - \frac{A+\alpha^F S}{0.161\,V}$$

$$= \frac{A}{0.161\,V} - \frac{A}{0.161\,V} + \frac{\alpha^F S}{0.161\,V}$$

Therefore, $\frac{1}{T_1} - \frac{1}{T_2} = \frac{\alpha^F S}{0.161\,V}$

$$\Rightarrow \alpha' = \frac{0.161V}{S}\left[\frac{1}{T_1} - \frac{1}{T_2}\right] \text{ ------ (3)}$$

Knowing the quantities on the right-hand side of eq. 3, the absorption coefficient α' of the absorbing material can be calculated.

Absorption Coefficients of Some Materials

Material	**Absorption coefficient per m^2 at 500 Hz**
Open window	1.00
Ventilators	0.10 to 0.50
Curtains with heavy folds	0.40 to 0.75
Audience (One adult in an upholstered seat)	0.46
Concrete	0.17
Marble	0.01

RADIOMETRY

Definition of radiometry

Radiometry is the scientific field that deals with the measurement and study of electromagnetic radiation, including visible light, infrared, ultraviolet, and other forms of electromagnetic waves.

It encompasses various principles and techniques used to quantify and describe the characteristics of radiation, such as its intensity, flux, spectral distribution, and energy.

Review of Electromagnetic (EM) spectrum

The electromagnetic (EM) spectrum is a continuum of all electromagnetic waves arranged by their frequencies and wavelengths. It encompasses a vast range of electromagnetic radiation, from extremely low frequencies with long wavelengths, such as radio waves, to extremely high frequencies with short wavelengths, like gamma rays.

The review of the different regions of the EM spectrum:

Radio Waves:

Frequency range: $< 3 \times 10^{11}$

Wavelength range: > 1 mm

Applications: Broadcasting, telecommunications, radar, and radio astronomy.

Microwaves:

Frequency range: $3 \times 10^{11} - 10^{13}$ Hz

Wavelength range: 1 mm – 25 μm

Applications: Cooking, wireless communications, satellite communications, and radar.

Infrared Radiation:

Frequency range: $10^{13} - 10^{14}$Hz

Wavelength range: 25 μm – 2.5 μm

Applications: Thermal imaging, remote controls, night vision, and some medical applications.

Visible Light:

Frequency range: $4 \times 10^{14} - 7.5 \times 10^{14}$Hz

Wavelength range: 750 nm to 400 nm

Applications: Human vision, photography, and optical communications.

Ultraviolet (UV) Radiation:

Frequency range: $10^{15} - 10^{17}$ Hz

Wavelength range: 400 nm – 1 nm

Applications: Sterilization, fluorescent lighting, and some medical treatments.

X-rays:

Frequency range: $10^{17} - 10^{20}$ (approximately)

Wavelength range: 1 nm – 1 pm (approximately)

Applications: Medical imaging (X-ray radiography), security scanning, and industrial applications.

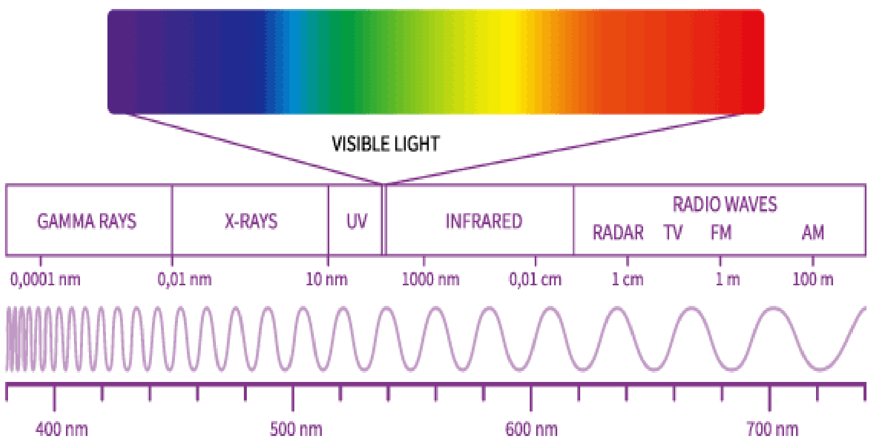
Gamma Rays:

Frequency range: $10^{20} - 10^{24}$ (approximately)

Wavelength range: $< 10^{-12}$ m (approximately)

Applications: Cancer treatment (radiation therapy), nuclear medicine, and scientific research.

Each region of the EM spectrum interacts with matter in different ways, leading to a wide range of applications in various scientific, industrial, and everyday contexts. The study and understanding of the EM spectrum are crucial for many fields, including astronomy, telecommunications, medicine, and environmental monitoring.



Radiant Energy

Radiant energy is the amount of heat radiated (E) emitted by a black body for a second per unit area which is directly related to the fourth power of its absolute temperature (T).

The Radiant heat energy (E) formula is articulated as, $\mathbf{E \propto T^4}$ **or** $\mathbf{E = \sigma T^4}$

Where, Stefan's constant $\sigma = 5.67 \times 10^{-8}\ W/m^2/K^4$, T is absolute temperature of the body (K)

Radiant Power

Radiant power also known as radiant flux or radiant energy flux.

It is the amount of radiant energy emitted, transmitted, or received per unit of time.

The unit of radiant power is the watt (W), which represents joules per second (J/s).

Mathematically, radiant power (P) can be expressed as:

$$P = dE / dt$$

Where: P = Radiant power (in watts, W) , dE = Change in radiant energy (in joules, J), dt = Change in time (in seconds, s)

Radiant intensity

Radiant intensity (I) is a measure of the radiant power emitted, transmitted, or received by a point source in a particular direction.

- It represents the amount of radiant power per unit solid angle.
- The unit of radiant intensity is watts per steradian (W/sr).

Mathematically, radiant intensity (I) can be expressed as:

$$I = dP / d\Omega$$

Where: I = Radiant intensity (in watts per steradian, W/sr) dP = Change in radiant power (in watts, W) $d\Omega$ = Change in solid angle (in steradians, sr)

Radiance

Radiance (L) is a fundamental radiometric quantity that describes the amount of radiant power emitted by a surface per unit area, per unit solid angle, and per unit wavelength interval.

- It characterizes the directional distribution of radiant flux at a specific point on a surface.
- The unit of radiance is watts per square meter per steradian per square meter ($W/(m^2 \cdot sr \cdot m^2)$).
- Mathematically, Radiance (L) at a given wavelength (λ) in a particular direction,

$$L = d^2 \Phi / (dA \cdot d\Omega \cdot d\lambda \cdot \cos(\theta))$$

Where:

- $d^2 \Phi$ = Change in radiant flux (in watts, W) incident on or emitted by an infinitesimal area (dA) of the surface within a small solid angle ($d\Omega$) and wavelength interval ($d\lambda$).
- dA = Infinitesimal area (in square meters, m^2)
- $d\Omega$ = Infinitesimal solid angle (in steradians, sr)
- $d\lambda$ = Infinitesimal wavelength interval (in nanometers, nm)
- θ = Angle between the surface normal and the direction of the radiance (in degrees)

Radiant Exitance (radiosity or radiant emittance)

Radiant Exitance is a radiometric quantity that describes the total radiant power emitted or radiated by a surface per unit area.

- It represents the amount of radiant energy leaving a surface in all directions.
- The unit of radiant exitance is watts per square meter (W/m^2).

Mathematically, radiant exitance (M) can be expressed as: $M = d\Phi / dA$

Where: M = Radiant exitance (in watts per square meter, W/m^2) $d\Phi$ = Change in radiant flux (in watts, W) leaving the surface within a small change in time (dt). dA = Infinitesimal area (in square meters, m^2)

Definition of spectral quantities

Spectral radiant power: Spectral radiant power is the amount of radiant power emitted, transmitted, or received per unit wavelength interval at a specific wavelength.

Spectral radiant intensity: Spectral radiant intensity is the amount of radiant power emitted per unit solid angle and per unit wavelength interval.

Spectral radiance: Spectral radiance is the amount of radiant power emitted, transmitted, or received by a surface per unit projected area, per unit solid angle, and per unit wavelength interval.

Spectral irradiance: Spectral irradiance is the amount of radiant power incident on a surface per unit projected area and per unit wavelength interval.

Reflectance and transmittance

Reflectance: Reflectance is the proportion of incident radiation that is reflected by a surface or material.

It is a measure of how much light or radiation is "bounced off" a surface rather than being absorbed or transmitted through it.

Reflectance is often expressed as a percentage or a decimal value between 0 and 1.

Transmittance: Transmittance is the proportion of incident radiation that passes through a material without being absorbed or reflected. It is a measure of how much light or radiation is able to "transmit" through a material. Like reflectance, transmittance is often expressed as a percentage or a decimal value between 0 and 1.

It can shown that, $T + R + A = 1$, where T=transmittance, R=reflectance, and A=absorptance.

PHOTOMETRY

Photometry is a branch of science that deals with the measurement of light and its properties, particularly in terms of human visual perception. It focuses on quantifying the intensity of light, its distribution, and its various attributes as perceived by the human eye. Photometry plays a crucial role in fields such as lighting design, optics, astronomy, and vision science.

Luminous energy

Luminous energy is the amount of energy emitted over a specific time period by a light source that is perceived by the human eye.

Luminous energy is typically measured in a unit called the "lumen-second" (lm-s) or "talbot" (T).

It takes into account the spectral sensitivity of the human eye, which is most sensitive to light in the green-yellow region of the spectrum.

Luminous Flux: Luminous flux is the total amount of visible light emitted by a light source per unit time in all directions.

Luminous flux is measured in lumens (lm).

Luminous intensity:

Luminous intensity is a photometric quantity that measures the amount of visible light emitted from a source in a particular direction.

The SI unit of luminous intensity is the candela (cd).

Luminance:

Luminance is the amount of visible light emitted by a surface per unit area and per unit solid angle in that direction.

The SI unit of Luminance is candelas per square meter (cd/m^2), which is equivalent to nits.

One nit is equal to one candela per square meter.

Luminous Exitance (luminous emittance):

Luminous exitance is a photometric quantity that measures the total visible light emitted or reflected by a surface per unit area.

It is a fundamental concept in photometry and is used to describe the light output of a surface.

Luminous exitance (M) is given by $M = d\Phi/dA$

Where: M is the luminous exitance (in lumens per square meter or lux), $d\Phi$ is the total luminous flux emitted or reflected by the surface (in lumens), dA is the differential area of the surface (in square meters)

Relationship between lumen and watt

Lumen (lm) and watt (W) are both units of measurement, but they represent different characteristics of light sources.

Lumen (lm): Lumen is a unit of measurement that quantifies the total amount of visible light emitted by a light source. It measures the brightness or luminous flux of the light.

Watt (W): Watt is a unit of measurement for power consumption or energy consumption. It indicates the rate at which energy is used or produced.

Candela

A light has a luminous intensity of 1 candela if it emits 1 lumen (1 lm per steradian.)

Illumination or Intensity of illumination (E)

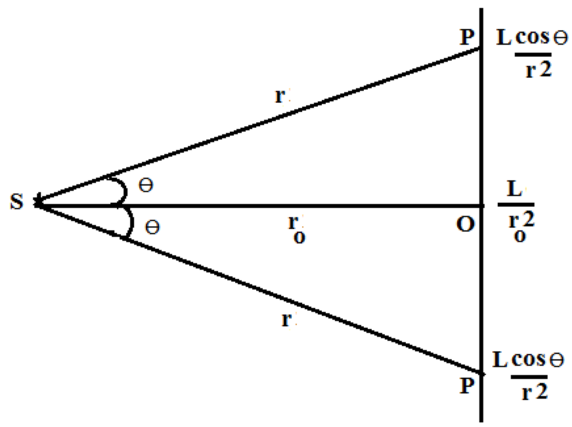
The luminous flux incident normally per unit area of the surface is called illumination or intensity of illumination.

Lambert's Cosine Law (Cosine Law)

It states that the Intensity of the illumination is directly proportional to the cosine of angle of incidence and inversely proportional to the square of the distance between surface and the source.

For any Θ, $I=\frac{L\cos\theta}{r^2}$ where, L is the luminous intensity ($L=\frac{\emptyset}{4\pi}$)

Θ=0, Then intensity of illumination, $I=\frac{L}{r_o^2}$



Inverse Square Law

It states that the illumination of surface is inversely proportional to the square of distance between source and light surface (d).

$$E=\frac{I}{d^2}$$

Questions

1. Define Photometry and explain photometric quantities.

2. Elucidate the Impact of Noise in Multi-storied buildings.

3. For an empty assembly hall of size 20 x15 x 10 cubic meter with absorption coefficient 0.106. Calculate reverberation time.

4. Define reverberation and reverberation time and hence derive Sabines Formula.

5. Mention the conditions for good acoustics.

6. Define the five spectral quantities.

7. Give the qualitative explanation of radiometric quantities such as Radiant energy, radiant power, radiant intensity, radiance, radiant existence etc along with respective equations.
8. Describe Reflectance and transmittance.
9. Explain the impact of noise in Multi-storied buildings.
10. Discuss the Factors affecting acoustics of buildings and remedial measures.
11. Explain Cosine law and inverse square law.
12. The reverberation time is found to be 1.5 second for an empty hall and it is found to be 1 second when a curtain cloth of $20m^2$ is suspended at the center of the hall. If the dimensions of the hall are 10 x 8 x 6 m3 calculate the coefficient of absorption of the curtain cloth.

****

MODULE -4

PHOTONICS

Syllabus:

LASER

Properties of a LASER Beam, Interaction of Radiation with Matter, LASER action, Population Inversion, Metastable State, Requisites of a LASER System, Semiconductor LASER, LASER Range Finder, LIDAR, Road Profiling, Bridge Deflection, Speed Checker, Numerical Problems.

OPTICAL FIBER

Principle and Construction of Optical Fibers, Acceptance angle and Numerical Aperture (NA), Expression for NA, Modes of Propagation, Attenuation and Fiber Losses, Fiber Optic Displacement Sensor, Fiber Optic Temperature Sensor, Numerical Problems.

LASERS

Laser is the acronym for Light Amplification by Stimulated Emission of Radiation.

Properties of Lasers

1. The laser light is very nearly monochromatic.

2. The laser light is coherent with the waves all exactly in phase with one another.

3. Directionality**:** Laser beam is highly directional. It hardly diverges. This property is useful to measure long distance with higher accuracy.

4. Intensity: Laser is extremely intense; hence by Laser we can achieve very high energy density.

Interaction of Radiation with Matter

When radiation interacts with matter, it leads to the transition of an atom from one energy state to another.

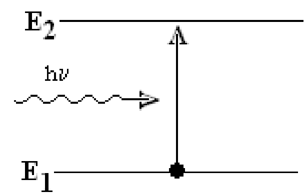
Consider two energy states E_1 and E_2 $(E_2 > E_1)$ of a system. An electron at the energy state E_1 is excited to E_2 when it absorbs a light photon of energy $\Delta E = (E_2 - E_1)$. If an electron makes a transition from the higher energy state E_2 to E_1, a light photon of energy $\Delta E = E_2 - E_1$ is emitted. In both the case the frequency of the photon involved is $\nu = \frac{\Delta E}{h} = \frac{E_2 - E_1}{h}$

There are three possible ways in which interaction of radiation and matter can take place.

1. Induced (stimulated) absorption:

"The process in which an atom in a lower energy state is raised to a higher energy state by absorbing a suitable photon is called stimulated absorption."

Consider two energy states with energies E_1 and E_2. Let a photon of energy $\Delta E = E_2 - E_1$ be incident on the atom. The atom absorbs the energy of the photon and its energy becomes equal to $E_1 + \Delta E = E_2$. Hence it makes a transition to the excited state E_2. This is called induced absorption.



Induced Absorption

Atom + photon → atom*

The number of such absorptions per unit time per unit volume is called the rate of absorption.

$\therefore$ Rate of absorption $\propto N_1 U_\upsilon$

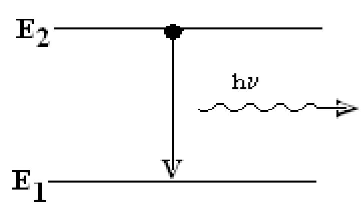
Or Rate of absorption = $B_{12} N_1 U_\upsilon \rightarrow$ (1)

Where $B_{12} \rightarrow$ Einstein's coefficient of induced absorption.

2. Spontaneous emission:

The process in which an atom in the higher energy state falls to the lower state by emitting a photon on its own is called spontaneous emission.

Consider an atom in the excited state, the atom voluntarily emits a photon of energy ΔE equal to $(E_2 - E_1)$ and falls to the energy state E_1. The emission where an atom emits a photon without any aid by external agency is called spontaneous emission.



Spontaneous Emission

The photons emitted may have any direction and phase. Hence they are incoherent.

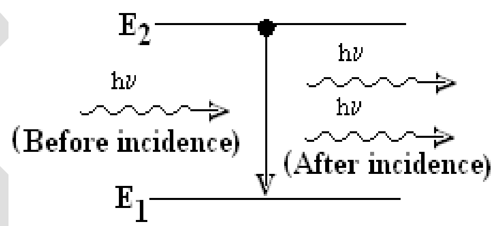
Atom*→ atom + photon

Rate of spontaneous emission = $A_{21} N_2$ ------------ (2)

where $A_{21} \rightarrow$ Einstein's coefficient of spontaneous emission

3. Stimulated emission:

"The process of the emission of a photon by a system under the influence of an incident photon of suitable energy, due to which the system transits from a higher energy state to a lower energy state is called stimulated emission."



Stimulated Emission

Consider an atom in the exited state with energy E_2. Let a photon of energy $\Delta E = E_2 - E_1$ interacts with this atom. As a result, the atom emits a photon and transits to the lower energy state. The emitted photon will have same phase, energy and direction of movement as that of the incident photon." The electromagnetic waves associated with the two photons will have same phase and thus they are coherent. This kind of emission is responsible for laser action.

Atom* + photon →Atom+ 2 photons

The rate of stimulated emission $= B_{21} N_2 U_\upsilon$ --------------- (3)

where B_{21} is the Einstein's coefficient of stimulated emission.

LASER ACTION

The atom during stimulated emission process emits a photon and transits to the lower energy state. The emitted photon will have same phase, energy and direction of movement as that of the incident photon resulting in two photons of similar properties. These two photons induce stimulated emission of 2 atoms in excited state, there by resulting in 4 photons. These 4 photons induce 4 more atoms and give rise to 8 photons etc., as shown in figure.

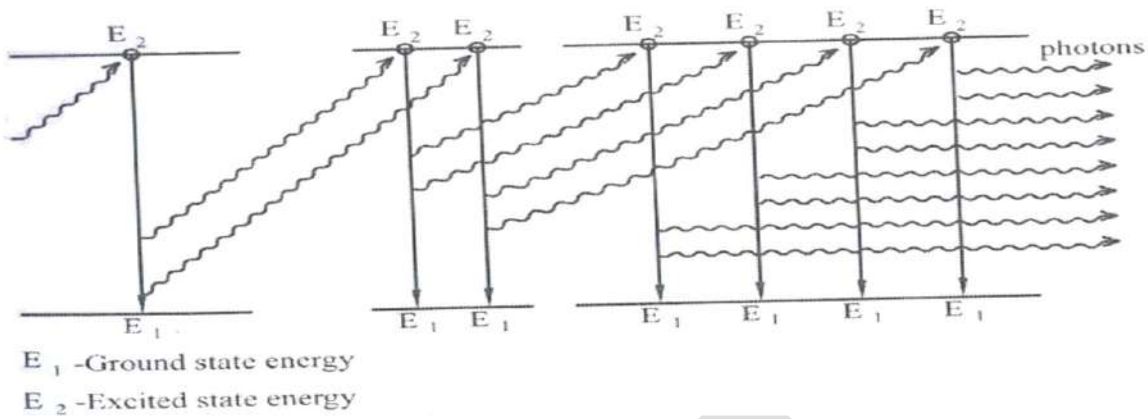


Fig: Amplification in Laser process

Condition for Laser action:

1. **Population inversion**

"It is the state of a system in which the number of atoms in the higher energy state is greater than the number of atoms in the lower energy state."

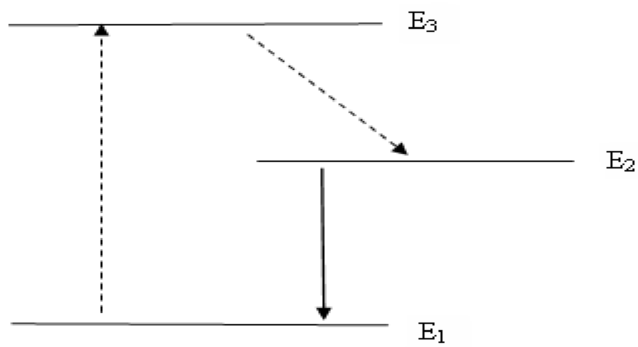
Under normal condition, the population is more in the lower state. But for stimulated emission, and hence for lasing action, more atoms must be present in the exited state. This can be achieved by some artificial means i.e. by providing energy in to the active medium of the laser system.

2. **Metastable state**

Under normal condition, population inversion doesn't exist. However, it is possible to achieve the population inversion in certain systems which possess a special exited state called **metastable state.**

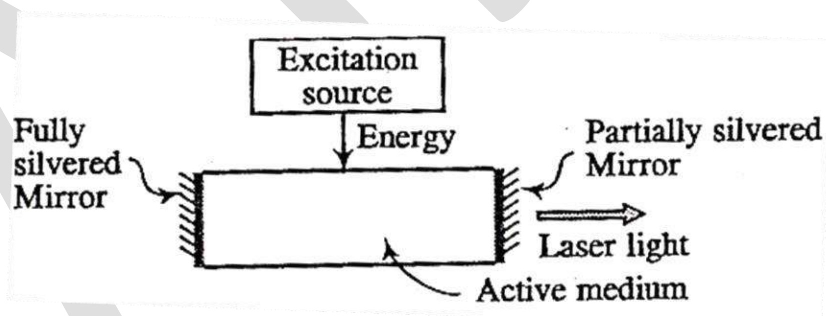
It is an exited state that is different from the ordinary exited state. The atoms which are excited to the higher energy states remain for a short duration of 10^{-8} sec and return to lower energy state. In case the state at which the atom is exited is a metastable state, then it stays there for a longer time of about 10^{-3} to 10^{-2} sec. This property helps in achieving population inversion.

Three Level Laser System



Consider 3 energy levels E_1, E_2, and E_3 of an atomic system. Let E_2 be a metastable state. By supplying suitable external energy, the atoms are exited from E_1 to E_3. The atoms in E_3 undergo spontaneous transition to E_1 and E_2 rapidly. Since E_2 is a metastable state, the atoms in this state stay for a longer time duration because of which the population in E_2 increases and population inversion is created. Once the population of E_2 exceeds that of E_1, stimulated emission takes place. The photons emitted are all identical with respect to phase, wavelength and direction and grow to a large number which is the laser light.

Requisites of Laser System



1) **Excitation mechanism:** An excitation mechanism/source provides energy in an appropriate from for pumping the atoms to higher energy levels (xenon flash lamp). If the pumping is achieved by light energy input, then it is called optical pumping (Ruby laser).If the pumping is achieved by electrical energy input, then it is called electrical pumping (He-Ne laser).

2) **Active medium:** A medium in which light gets amplified is known an active medium. The medium may be solid, liquid or a gas. A part of the input energy is absorbed by the active medium in which population inversion occurs at a certain state.

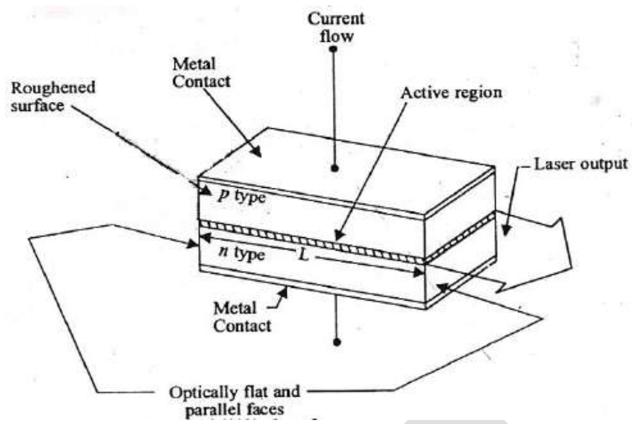
3) Laser cavity: It provides the feedback necessary to tap certain permissible part of laser energy from the active medium. It consists two mirrors along with the active medium called cavity. The mirrors reflect the photons to and fro through the active medium. A laser device consists of an active medium bound between two parallel mirrors of high reflectivity. Inside the cavity two types of waves exist, one moving towards the right and other to the left. These waves interfere constructively or destructively depending on the phase difference.

In order to arrange for constructive interference, the distance 'L' between the two mirrors should be such that the cavity should support an integral number of half wavelength, i.e. $L = m\frac{\lambda}{2}$, where L is the distance between the two mirrors and m is an integer >0. This results in the amplification of stimulated emission of radiation which is the laser light.

SEMICONDUCTOR DIODE LASER

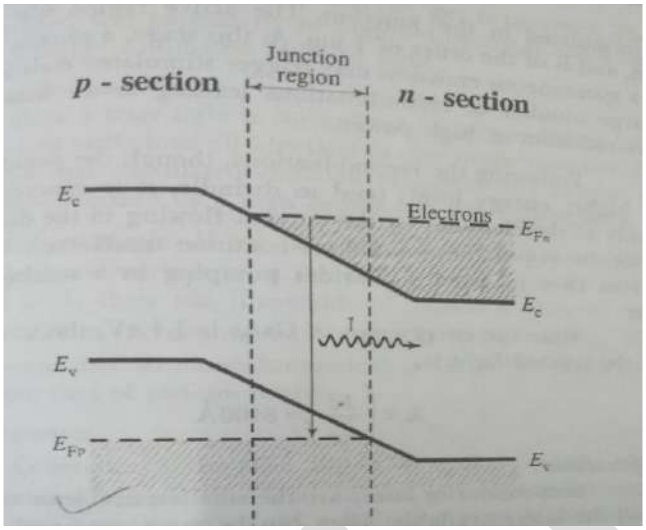
Construction:

A semiconductor diode laser is a specially fabricated p-n junction device that emits coherent light when it is forward biased. The direct band gap Gallium Arsenide single crystal is used for the construction of laser. The n-section is formed by doping with tellurium, whereas p-section is formed by doping with zinc. The doping concentration is high and is of the order of 10^{17} to 10^{19} dopants atoms/cm^3. The diode is extremely small in size with sides of the order of 1mm. The junction lies in the horizontal plane through the centre. The top and bottom faces are metalized and ohmic contacts are provided to pass current through the diode. The front and rear faces are polished parallel to each other and perpendicular to the plane of the junction. The other two faces are roughened to prevent lasing action in that direction. The active region consists of a layer of about 1 μm thickness.



Working:

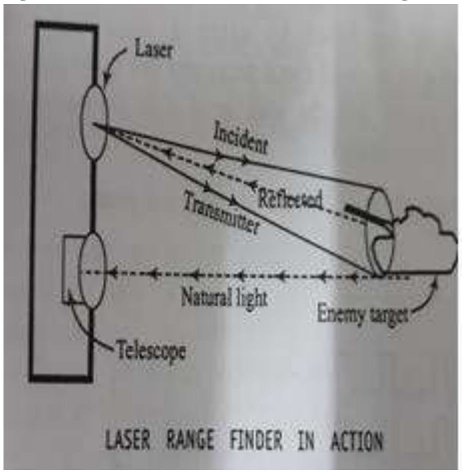
The population inversion can be achieved in a semiconductor by using it in the form of a heavily doped p-n junction and forward biasing it. With very high doping on n-side, the donor levels as well as a portion of the conduction band (CB) are occupied by electrons and the Fermi level lies within the CB. When a forward bias is applied, the fermi energy levels shifts and the new distribution is as shown in figure. Electrons and holes are injected in to the depletion region, where they appear in large number. At low forward current, the electron-hole recombination causes spontaneous emission of photons. As the current increases and reaches a threshold value, the carrier-concentration in the depletion region will reach very high values. The upper levels in the depletion region are having high population of electrons while the lower levels are having large number of holes. This is the state of population inversion. The narrow region where the state of population inversion is achieved is called inversion or active region. Thus the forward bias current plays the role of pumping agent in semiconductor laser. The photons that propagate in the junction plane induce the conduction electrons to jump in to the vacant state of VB. The stimulated electron hole recombination causes emission of coherent radiation.



Applications of Laser

LASER range finder in defense:

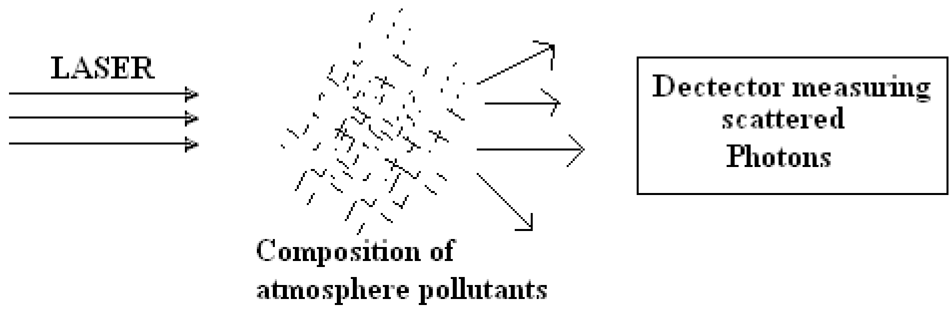
A high-power pulsed laser beam from Nd-YAG laser is directed towards the enemy target. The beam bounces from the surface of the target. Part of reflected beam called echo is received by the receiver. Inside the receiver there is an interface filter. The filter tunes the background noise and the small signal is amplified using photo-multiplier.



The range finder high speed clock measures the exact time since the pulse left the laser and until it is received, and then converts it into distance.

Here the distance is calculated usually within 1% of the actual distance. The range finders are also used for continuous tracking and ranging of missiles and aircrafts from ground or from air.

LIDAR (Measurement of pollutants in the atmosphere)



There are various types of pollutants in the atmosphere which includes oxides of nitrogen, carbon monoxide, sulphur oxide, dust, smoke, fly ash etc. In conventional techniques, samples of the atmosphere are collected and then chemical analysis is carried out to find the composition of the pollutants. But this is not a real time data.

In the application of laser for measurement of pollutants, the principle is very much similar to that of RADAR. This technique is called LIDAR which stands for light detection and ranging. Here a pulsed laser is used as the source of light and the light scattered back is detected by a photodetector. The distance to the matter and the concentrations of the matter is obtained by this method.

Absorption technique can also be utilized to study the atmospheric pollutants. Each material absorbs light of characteristic wavelength and from the absorption spectrum, the existence of the material can be identified.

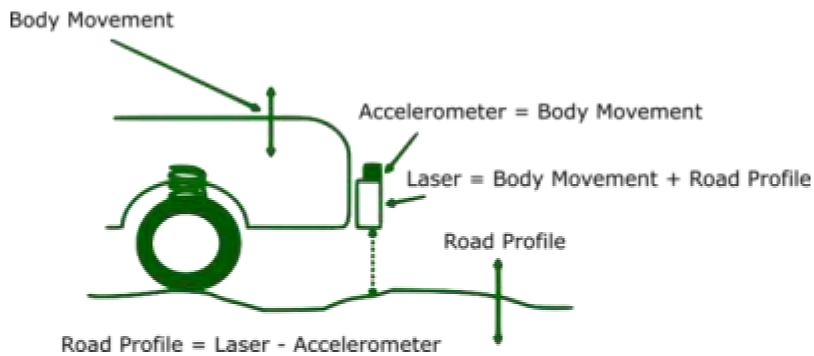
Road Profiling

Laser road profiling is a technique used for the precise measurement and analysis of road surface characteristics. It involves the use of laser technology to gather detailed data about the profile and roughness of roads, highways, and other paved surfaces. These measurements are crucial for assessing the condition of roadways, identifying potential hazards, and planning maintenance and rehabilitation efforts. Laser road profiling involves the following steps.

a) Laser Measurement: Laser road profiling systems utilize laser sensors mounted on vehicles or specialized equipment to scan the road surface. These sensors emit laser beams and measure the time it takes for the beams to bounce back after hitting the road. By analyzing the reflected signals the system can determine the road's elevation and roughness at various points along its length.

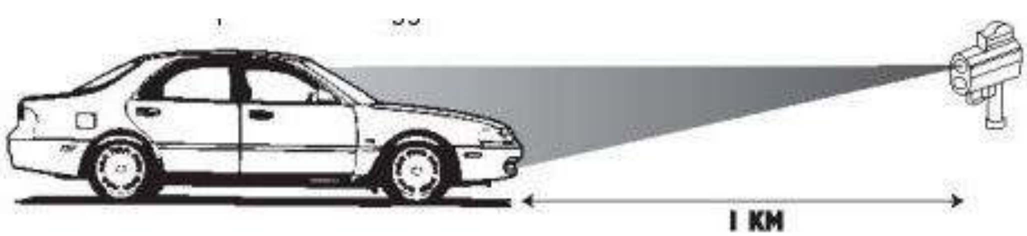
b) Profile Analysis**:** The collected data is processed to create a detailed profile of the road surface. The profile reveals variations in height, such as bumps, depressions, and undulations, providing an accurate representation of the road's condition. This information is vital for assessing ride quality, identifying potential safety hazards, and planning necessary repairs or resurfacing.

c) Roughness Measurement**:** Laser road profiling systems also measure the roughness of the road surface. Roughness refers to irregularities on the road that can cause discomfort to drivers and accelerate wear and tear of vehicles. By quantifying roughness parameters, such as International Roughness Index (IRI), or Ride Number, engineers can evaluate the road's condition and prioritize maintenance and improvement activities.



Speed Checker

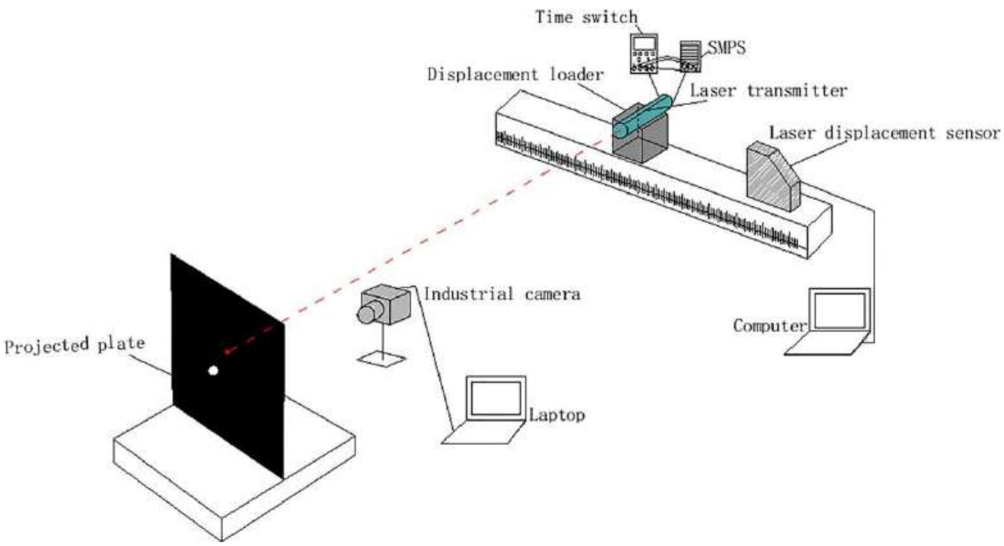
Laser speed checking is a technology used by law enforcement agencies to measure the speed of vehicles accurately. It utilizes laser beams to determine the speed of a moving object by measuring the time it takes for the laser beam to travel to the vehicle and back. The laser speed checking devices emit a narrow beam of infrared laser light towards a vehicle. The device measures the time it takes for the laser beam to be reflected back to the device. By knowing the speed of light, the device can calculate the speed of the target vehicle based on the time it takes for the beam to travel and return.



Bridge deflection

Bridge deflection refers to the amount of deformation or bending experienced by a bridge under the load it carries. Monitoring bridge deflection is crucial for ensuring the structural integrity and safety of the bridge.

Laser technology can be utilized for measuring bridge deflection. The basic principle involves the use of laser beams and sensors to detect and quantify the displacement or movement of the bridge. Laser deflection measurement offers several advantages, including non-contact measurement, high accuracy, and the ability to monitor large areas of the bridge. It provides valuable data for evaluating the performance and safety of bridges, enabling engineers and authorities to take appropriate actions for maintenance and structural improvements.



****

OPTICAL FIBER

Introduction

A conventional method of long distance communication uses radio waves (10^6 Hz) and micro waves (10^{10} Hz) as carrier waves. A light beam acts as a carrier wave which is capable of carrying far more information, since optical frequencies are extremely large (10^{15} Hz).

Soon after the discovery of laser, some preliminary experiments in propagation of information carrying light waves through the open atmosphere were carried out, but it was realized that the unwanted elements such as rain, fog etc, leads to adverse effects. Thus, in order to have an efficient and dependable communication system one would require a guiding medium in which the information carrying light waves could be transmitted. This resulted in the development of optical fibers which are an efficient guiding medium for laser light.

Optical fibers are essentially light guides used in optical communication as waveguides. Use of light waves in place of radio and microwave have improved the speed of communication.

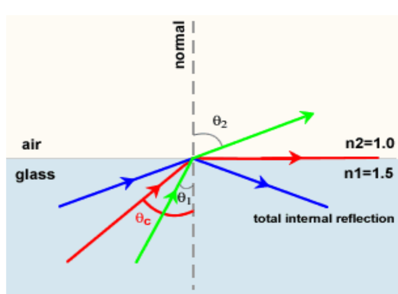
Optical fibers

An optical fiber is a cylindrical dielectric waveguide that transmits light along its axis through the process of total internal reflection.

Total internal reflection

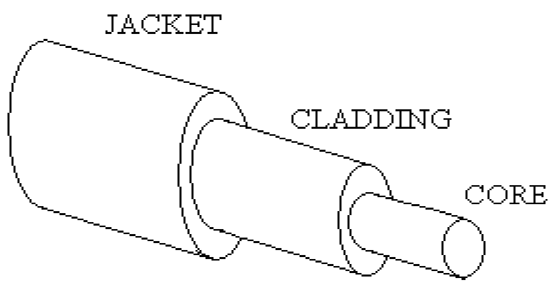
The basic principle of an optical fiber is multiple total internal reflections.

When a ray of light travel from denser to a rarer medium, at an angle of incidence greater that critical angle Θ_c, the ray is not refracted but it is reflected into the same denser medium. This property is called total internal reflection.

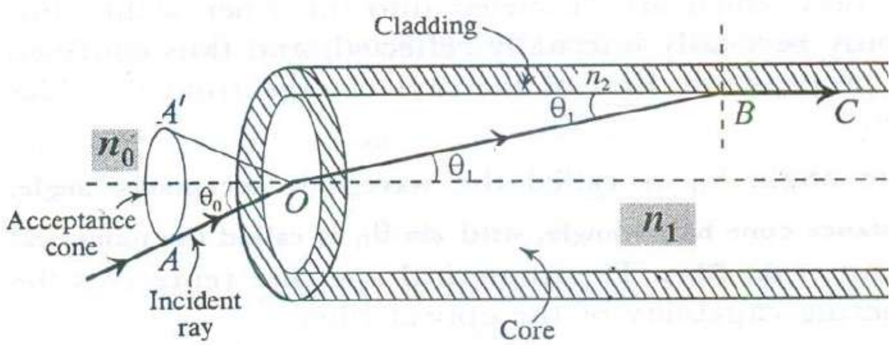


Structure of Optical Fiber:

An optical fiber consists of a very thin transparent cylindrical core having refractive index n_1 surrounded by a cylindrical shell called cladding of slightly lower refractive index n_2. The core-cladding system is surrounded by a plastic jacket.



Expression for Angle of Acceptance and Numerical Aperture:



Consider an optical fiber into which light is launched at one end from a medium of RI $\mathbf{n_0}$. Let $\mathbf{n_1}$be the RI of core and $\mathbf{n_2}$be that of the cladding. Assume that a ray of light enters the fiber at an angle θ_0 with respect to the axis of the fiber. The light ray refracts at an angle θ_1 and strikes the core – cladding interface at an angle of $(90 - \theta_1)$. If $(90 - \theta_1)$ is greater than the critical angle for the core – cladding interface, the ray undergoes total internal reflection at the interface.

It is clear from the figure that any light ray which enters the core at an angle less than θ_0 will undergo total internal reflection at the core – cladding interface and will propagate along the fiber. The angle θ_0 is called the acceptance angle. It is the maximum angle that a light ray can have relative to the axis of the fiber and thus propagate down the fiber. Sine of the acceptance angle θ_0, $\sin\theta_0$, is called the numerical aperture (NA) of the fiber. It represents the light gathering capacity of the optical fiber.

Applying Snell's law at 'O'

$$\frac{\sin\theta_0}{\sin\theta_1} = \frac{n_1}{n_0} \rightarrow (1)$$

Applying Snell's law at 'B'

$$n_1 \sin(90-\theta_1) = n_2 \sin 90$$

$$\cos\theta_1 = \frac{n_2}{n_1} \rightarrow (2)$$

Rewriting equation (1),

$$\sin\theta_0 = \frac{n_1}{n_0}\sin\theta_1$$

$$= \frac{n_1}{n_0}\sqrt{1-\cos^2\theta_1}$$

$$= \frac{n_1}{n_0}\sqrt{1-\frac{n_2^2}{n_1^2}}$$

$$\sin\theta_0 = \frac{\sqrt{n_1^2-n_2^2}}{n_0} \rightarrow (3)$$

If the medium surrounding the fiber is air, then $n_0 = 1$

$$\therefore \sin\theta_0 = \sqrt{n_1^2-n_2^2}$$

If θ_i is the angle of incidence of an incident ray w.r.t. the axis of the fiber, then ray will be able to propagate,

if $\theta_i \langle \theta_0$

if $\sin\theta_i \langle \sin\theta_0$

or $\boxed{\sin\theta_i \langle N.A.}$

This is the **condition for propagation.**

Modes of propagation

Light propagates as an electromagnetic wave through an optical fiber. All waves having ray directions above the critical angle will be trapped within the fiber due to total internal reflection. But all such waves do not propagate along the fiber. There are certain ray directions allowed for the propagation. These allowed ray directions or possible number of path of light in an optical fiber is known as modes of propagation. The paths are zigzag paths, except the axial direction. The number of modes that a fiber will support depends on the diameter of the core and wavelength of the wave being transmitted.

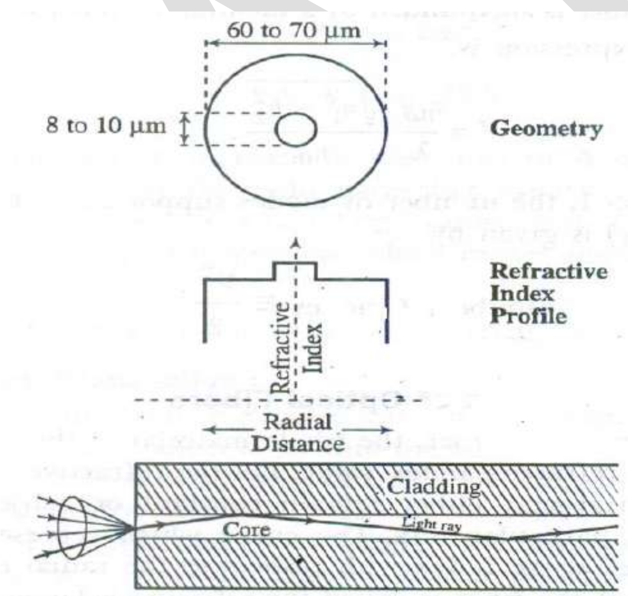
Refractive index (RI) profile

Refractive index profile is a curve which represents the variation of refractive index with respect to the radial distance from the axis of the fiber.

Types of optical fibers:

Depending on the RI profile and number of modes that a fiber can support, there are three types of optical fibers. They are:

1. **Step index single mode fiber:**



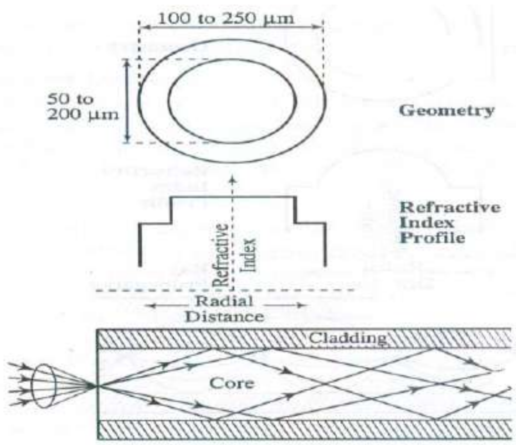
A step index single mode fiber has a core diameter of about 8 to 10 μm and external cladding diameter of 60 to 70 μm. The RI of the core has a uniform value. The cladding also has a uniform RI but slightly lesser than that of the core. The RI of the fiber changes abruptly at the core – cladding interface. Hence it is called a step index fiber. This fiber can support only one mode of propagation along its axis. Hence it is called a single mode fiber.

Due to narrow diameter of the fiber only laser can be used as the source of light with these fibers. There is no intermodal dispersion in the fiber. These are widely used in submarine cable systems.

2. Step index Multi mode fiber:

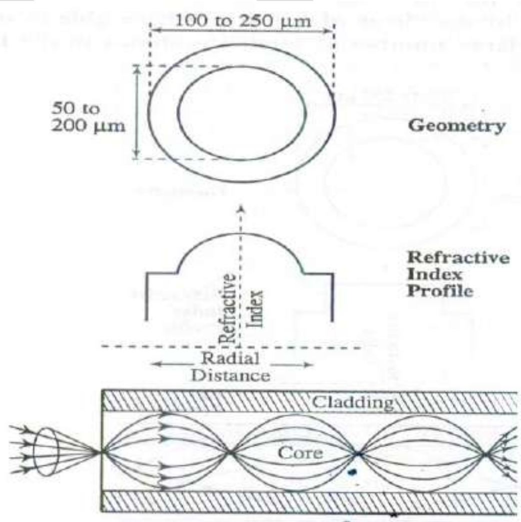
This fiber has a core diameter of 50 to 200 μm and a cladding diameter of 100 to 250 μm. The RI remains uniform in the core and cladding region. But the RI changes abruptly at the core – cladding interface. Because of larger diameter, this fiber allows many modes to propagate through it.

The step index multimode fiber can accept either a laser or LED as source of light. It is used in data links which has lower band width requirements.



3. Graded Index Multimode fiber:

It is a multimode fiber with a core consisting of concentric layers of different refractive indices. Therefore, RI of the core decreases with distance from the fiber axis. The RI of the cladding remains uniform. The RI profile and the modes of propagation are shown in the fig. Such a RI profile causes a periodic focusing of light propagating through the fiber. Either a laser or a LED can be the source for these fibers.



Normalized frequency (V – number):

It is the relation between fiber size, the refractive indices and the wavelength of light propagating through the fiber. It is given by,

$$V = \frac{\pi d}{\lambda}\sqrt{{n_1}^2 - {n_2}^2}$$

Where, $d \rightarrow$ diameter of the core; $n_1 \rightarrow$ RI of the core; $n_2 \rightarrow$ RI of the cladding;

$\lambda \rightarrow$ Wavelength of light.

Since $\sqrt{{n_1}^2 - {n_2}^2}$ = N.A. (numerical aperture), we can write,

$$V = \frac{\pi d}{\lambda} N.A.$$

The number of modes supported by a fiber is given by, $M_N = \frac{V^2}{2}$

Attenuation:

The loss of power suffered by the optical signal as it propagates through the fiber is called attenuation.

The attenuation or fiber loss is due to the following factors:

1. Absorption losses
2. Scattering losses
3. Radiation or bending losses

1. **Absorption Losses:**

The loss of signal strength occurs due to absorption of photons during its propagation. Photons are absorbed by:

a) Impurities in the silica glass of which the fiber is made of.
b) Intrinsic absorption by the glass material itself.

a. Absorption by impurities:

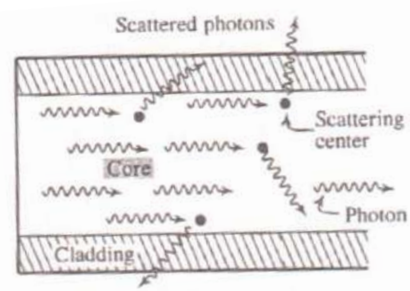
The impurities that are generally present in fiber glass are iron, chromium, cobalt, copper etc. During signal propagation when photons interact with these impurities, the electrons absorb the photons and get excited to higher energy levels. Later these electrons give up their absorbed energy in the form of light photons. But this is of no use, since these photons differ in wavelength and phase.

b. Intrinsic Absorption

The fiber material itself has a tendency to absorb light energy however small it may be. Hence there will be a loss and is known as intrinsic absorption.

2. **Scattering Losses:**

The optical power is lost due to the scattering of photons. This scattering is due to the non- uniformity in the density of the fiber material, which leads to the variation in the RI of the fiber. Structural inhomogenities and defects created in the fiber can also cause scattering. The loss of light energy by scattering is found to be wavelength dependent. It decreases with increase in the wavelength of light to be transmitted through the fiber.

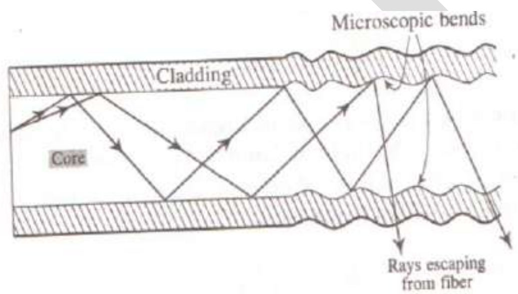


RAYLEIGH SCATTERING
Fig. 8

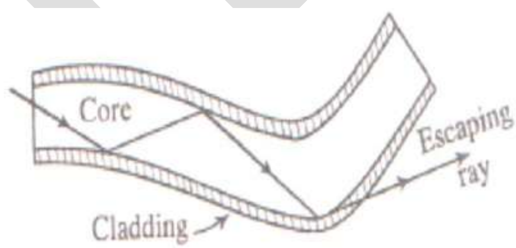
3. **Bending Losses (Radiation Losses):**

Radiation losses occur due to bending of fiber. There are two types of bends

a) Microscopic bends
b) Macroscopic bends



MICROSCOPIC BENDING LOSS



RADIATION LEAKS

Microscopic bends are caused during manufacturing as well as due to the applied stress on the fiber. Macroscopic bending arises during the installation of the fiber. At the point of a bend, light will escape to the surrounding medium due to the fact that the angle of incidence at that point becomes lesser than the critical angle.

To minimize these losses, the optical fiber has to be laid without sharp bends and they should be freed from the external stresses by providing mechanical strength through external coverage.

Attenuation Co-efficient:

Attenuation is the loss of power suffered by the optical signal as it propagates through the fiber. It is also referred as fiber loss.

Attenuation co-efficient or attenuation, $\alpha = -\frac{10}{L}\log(\frac{P_o}{P_i})$ dB/km

Where P_i is the optical power launched at the input and P_o the output power after traveling a distance L km.

Applications of optical fibers:

1. **Fiber Optic Temperature sensors (Phase modulated sensor)**

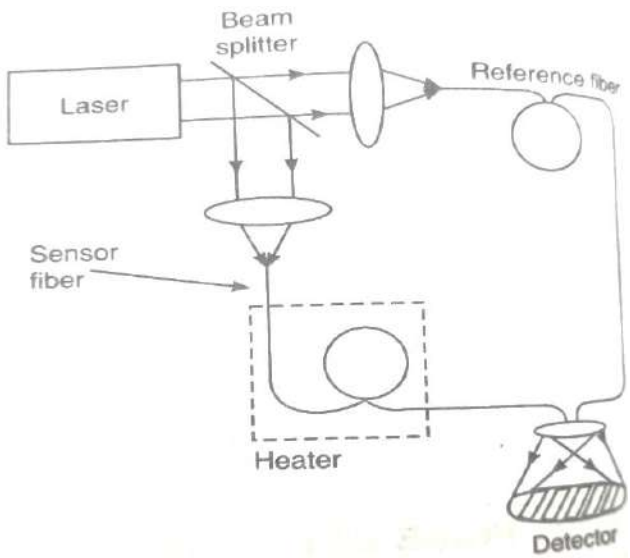
Fiber optic sensors are transducers, which generally consists of light source coupled with an optical fiber and a light detector held at the receiver end.

Principle: This temperature sensor is based on phase variation resulting due to the variation of refractive index of the optical fiber under the influence of temperature.

Construction: Figure shows the single mode fiber sensor arranged in what is known as the Mach Zehnder arrangement. Light source is laser. A beam splitter divides the light into two parts and sends light through the sensing fiber and the reference fiber. Light passing out of the two fiber element is fed to a detector, which measures the difference in phase of the two light waves. Accurate measurements of the temperature may be obtained from these patterns.

Working: Light from the source is divided into two parts by the beam splitter. One part is allowed through sensor fiber, and the other part is passed through the reference fiber. Light rays entering the fibres are coherent and have the same phase. Prior to heating, the optical path lengths of the two fiber elements are same and hence both the outputs will be in phase. When the sensor fiber is subjected to heating, the temperature causes a change in the refractive index of the optical fiber.

Therefore, the light coming out of the two fibers at the other end will have phase difference due to difference in optical path difference caused by heating. When the rays are superposed, they interfere and interference pattern will be observed. As temperature increases, the phase difference between the two outputs increases and is observed as a displacement of the fringe pattern. By determining the fringe displacement, we can determine the magnitude of temperature



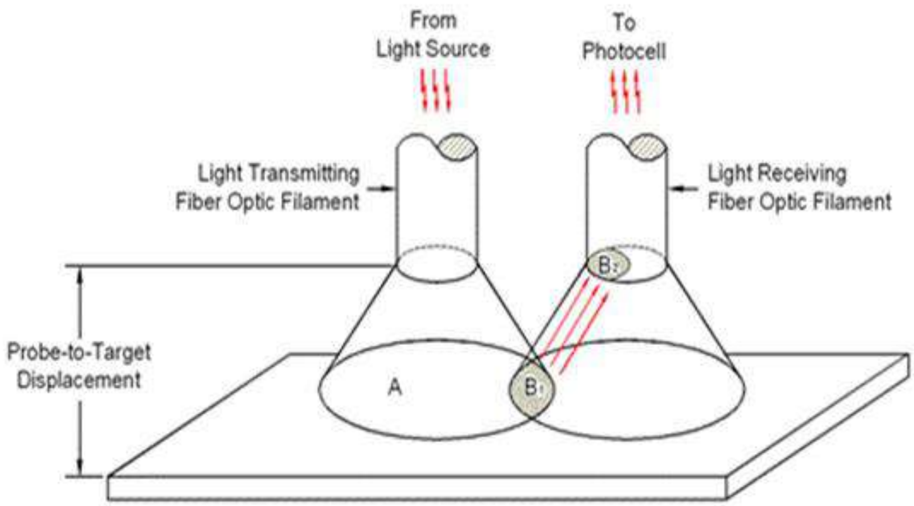
2. **Displacement Sensor**

Principle: It consists of pair of fiber optic elements, one carry light from the source to an object, whose displacement to be measured and the other to receive the light reflected from the object. Displacement of the target is measured with respect to the intensity modulation of the reflected light.

Construction: Two separate optical fibers are positioned adjacent to each other. One of them transmits light coming from a light source. The other fiber receives light reflected from the object under study and passes it onto a photo detector.

Working: Light from the transmitting fiber element is incident on the object under study. The light receiver fiber element is positioned adjacent to the transmitting fiber. If the gap between the object and the fiber element is zero, the light from the transmit fiber would be directly reflected back into itself and little or no light would go into the receiver fiber. When the object moves away, the gap increases and some of the reflected light is captured by the receiver fiber.

As the gap increases, a distance will be reached at which a maximum reflected light will be received. Further increase in the gap will result in a decrease in the light at receiver fiber which reduces the intensity in the signal output from the photo detector. By proper calibration, we can obtain the displacement of the object in terms of strength of the output signal of the photo detector.



Merits and demerits of optical communication:

The advantages of optical fiber communication include the following:

- Large amount of information can be transmitted per unit time in a fiber.
- Low attenuation allows data transmission for longer distances.
- The optical cable is resistance for electromagnetic interference.
- The size of the fiber cable is 4.5 times better than copper wires.
- The cables are lighter, thinner, and occupy less area compared with metal wires.
- Installation is very easy due to less weight.
- The optical fiber cable is very hard to tap because they don't produce electromagnetic energy. These cables are very secure while carrying or transmitting data.
- A fiber optic cable is very flexible, easily bends, and opposes most acidic elements that hit the copper wire.

The disadvantages of optical fiber communication include the following:

- The optical fiber cables are very difficult to merge & there will be a loss of the beam within the cable while scattering.
- The installation of these cables is cost-effective. They are not as robust as the wires. Special test equipment is often required to the optical fiber.
- Fiber optic cables are compact and highly vulnerable while fitting.
- These cables are more delicate than copper wires.
- Special devices are needed to check the transmission of fiber cable.

QUESTIONS

1. Discuss the construction and working of laser in LASER range finder and its application in defense.
2. Define Numerical Aperture and hence derive an expression for numerical aperture in terms of the RIs of core, cladding and the Surrounding.
3. Calculate the number of photons emitted per second for a LASER with power output 10mW given the wave length of fiber 690 nanometer.
4. Explain the construction and working of fiber optic temperature sensor.
5. Enumerate the requisites of a laser system and Describe the construction and working of Semiconductor Laser with a neat sketch and energy level diagram.
6. Calculate the attenuation coefficient for a fiber of length 2 km given the input and output optical power of the fiber 90 mW and 60 mW.
7. Discuss the interaction of radiation with matter and hence explain Laser Action.
8. Discuss the construction and working of optical fiber displacement sensor.
9. Give brief description of application of LASER in Road Profiling, Bridge Deflection and Speed Checker.
10. Define attenuation in fiber with the expression for attenuation coefficient and describe the various fiber losses.
11. Calculate the Numerical aperture and acceptance angle for an optical fiber of RI of core 1.5 and RI of cladding 1.45 placed in water of RI 1.33.

PROBLEMS

1. The average output power of laser source emitting a laser beam of wavelength 632.8nm is 5 mW. Find the number of photons emitted per second by laser source.

Hint:

$\Delta E = h\nu = hc/\lambda$

$N \times \Delta E = 5\times10^{-3}W$

(Ans: $\Delta E = 3.143\times10^{-19}$ J, $N = 1.59\times10^{16}$)

2. A pulsed laser emits photons of wavelength 780nm with 20 mW average power/pulse. Calculate number of photons contained in each pulse if pulse duration is 10ns.

Hint: Energy of each photon $\Delta E = h\nu = hc/\lambda$

Energy, $E = P\times t$

$N \times \Delta E = E$

(ANS: $\Delta E = 2.55\times10^{-19}$J, $E = 2\times10^{-10}$J, $N = 7.86\times10^{8}$)

3. A pulse from laser with power 1mW lasts for 10ns .If the number of photons emitted per second is 3.491×10^7, Calculate the wavelength of laser.
Hint: Energy of each photon $\Delta E = h\nu = hc/\lambda$

Energy, $E = P \times t$

$N \times \Delta E = E$

(ANS: $\lambda = 6943.6 \times 10^{-10}$ m)

4. The refractive indices of core and cladding are 1.50 and 1.48 respectively in an optical fiber. Find the numerical aperture and angle of acceptance.

Hint: N.A.= $\sqrt{(n_1^2 - n_2^2)}$

N.A= $\sin\theta_o$

(ANS: N.A. =0.244 and $\theta_o = 14.4^o$)

5 An optical fiber has a core material with RI 1.55 and its cladding material has RI 1.50. The light is launched into it in air. Calculate its N.A, and acceptance angle.

Hint: N.A.= $\frac{\sqrt{(n_1^2 - n_2^2)}}{n_o}$

(ANS: N.A= 0.39, $\theta_o = 23^o$)

6. The angle of acceptance of an optical fiber is 30^o when kept in air. Find angle of acceptance when it is in a medium of refractive index 1.33.

Hint: $\sin\theta_o = \frac{\sqrt{(n_1^2 - n_2^2)}}{n_o}$

$\sin\theta_o^I = \frac{\sqrt{(n_1^2 - n_2^2)}}{n_0^I}$

(ANS: $\theta_o = 0.5$, $\theta_o^I = 22^o$)

7. Find the attenuation in an optical fiber of length 500m, when a light signal of power 100mW emerges out of the fiber with a power of 90mW.

Hint: Fiber attenuation, $\alpha = -\frac{10}{L} log_{10}(\frac{P_{out}}{P_{in}})$dB/km

(ANS: α=0.915dB/km)

8.The attenuation of light in an optical fiber is 3.6dB/km.What fraction of its initial intensity remains after i)1km, ii) after 3km ?

Hint: Fiber attenuation, $\alpha = -\frac{10}{L} log_{10}(\frac{P_{out}}{P_{in}})$dB/km

(ANS :α=0.436, α=0.0832)

9. An optical glass fiber of refractive index 1.50 is to be clad with another glass to ensure internal reflection that will contain light traveling within 5º of the fiber axis. What maximum index of refraction is allowed for the cladding?

Hint : $n_1 \sin i = n_2 \sin r$ (Ans: $n_2 < 1.49$)

****

MODULE-5

Natural Hazards and Safety

Introduction

A hazard is a natural disaster that pertains to a natural phenomenon that causes injury/ loss of life or damage to property/environment.

A disaster is an event that occurs suddenly/unexpectedly in most cases and disrupts the normal course of life in the affected area. It results in loss or damage to life, property, or the environment. This Loss is beyond the coping capacity of the local affected population/society. And therefore requires external help.

Classification of hazards

There are many different ways of classifying hazards. One the basis of nature of origin, hazards are as follows:

(i) Natural hazards such as earthquakes or floods arise from purely natural processes in the environment.

(ii) Manmade hazards such as the toxicity of pesticides to fauna, accidental release of chemicals or radiation from a nuclear plant. These arise directly as a result of human activities.

Natural hazards: Natural disasters are further classified in the following categories:

(i) Geophysical: The phenomena originating from inside the earth as a result of the various geological, geophysical and tectonic activities. Examples: earthquakes, volcanic eruptions, landslides.

(ii) Hydrological: Events caused by imbalance in the normal hydrological cycle and/or overflow of bodies of water caused by wind set-up tectonic activities. These include, floods, costlal erosion, reverine erosion, mass wasting.

(iii) Meteorological: Events caused by short-lived/small to meso scale atmospheric processes (in the spectrum from minutes to days). These include, heat and cold waves, thunderstorms, hailstorms, blizzards, cyclonic and local storms.

(iv) Climatological: Events caused by long-lived/meso to macro scale atmospheric processes (in the spectrum from intra-seasonal to multi-decadal climate variability). These include, tropical cyclonic storm, extra tropical cyclonic storm, drought.

(v) Biological: A hazard caused by the exposure to living organisms and their toxic substances (e.g. venom, mold) or vector-borne diseases that they may carry. These include hazards caused by micro-organisms, insect infestation, animal accidents.

Man-made hazards:

Man-Made hazards are events that are caused by humans and occur in or close to human settlements. The events leading up to a man-made hazard may be the result of deliberate or negligent human actions, but their impact can be equally as devastating. These include technological hazards such as industrial hazards, transport hazards, infrastructural hazards, and social hazards such as terrorism, racial and religious conflicts, famines, and wars.

Earthquakes

An earthquake is a trembling of the ground that results from the sudden shifting of rock beneath the earth's crust. Earthquakes may cause landslides and rupture dams. Earthquakes occur along faults, which are fractures or fracture zones in the earth across which there may be relative motion.

The main characteristics of an earthquake are the following:

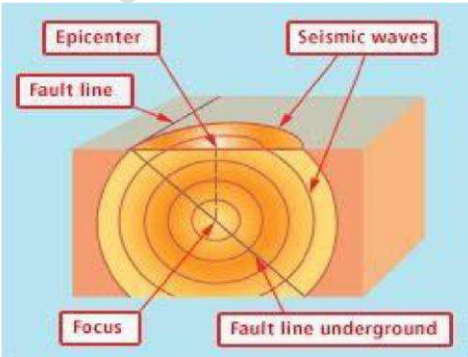
- They are sudden movements of the earth that happen in the internal layer of the earth.
- They happen naturally and spontaneously.
- They are caused by the collision of the tectonic plates.
- They move by means of vibrations that travel through the earth's crust.
- Can be measured by means of scales.
- Depending on their intensity, earthquakes can cause great destruction and death.

Physics of earthquakes

The forces generated in Earth's crust are typically described in terms of the shear stress and the shear strain. The shear stress is the force per unit area applied tangent to a plane. The shear strain is a dimensionless quantity that describes the distortion of a body in response to shear stress;

When the stress at a point in the crust exceeds a critical value, called the local strength, a sudden failure occurs. The plane along which failure occurs is called the fault plane and the point where failure initiates is called the focus. Typically, there is a sudden displacement of the crust at the fault plane following the failure and elastic waves are radiated. This is an earthquake.

For most earthquakes, the displacement occurs at an existing geological fault, that is, a plane that is already weak



Types of earthquakes

1.Tectonic Earthquakes

The earth's crust is composed of loose, cracked fragments of land referred to as tectonic plates. These plates are capable of moving slowly and gradually. The movement of these plates occurs in different forms; towards each other, away from each other, sliding past each other or colliding with each other. A huge tremor occurs when two moving tectonic plates slide over one another. This type of earthquake is known as a tectonic earthquake.

Tectonic earthquakes are the most prevalent kinds of earthquakes in the world. Its magnitude may be small or large. Tectonic earthquakes have caused most of the planet's mass destruction. Tremors triggered by tectonic earthquakes are always severe, and if their magnitude is high, they are capable of bringing down an entire city in seconds.

2. Volcanic Earthquakes

Compared to tectonic earthquakes, volcanic earthquakes are less prevalent. They typically take place before or after an eruption. Volcanic earthquakes come in two forms: long-period volcanic earthquakes and volcano-tectonic earthquakes. Volcano-tectonic earthquakes usually happen after a volcanic eruption. During an earthquake, magma erupts from inside the earth's crust leaving space behind. The space left after magma eruption must be filled. To fill it, rocks move toward the space resulting in severe earthquakes.

On the other hand, a long period of volcanic earthquake takes place after a volcanic eruption. Some days prior to the massive explosion, the magma inside the earth's crust experiences rapid changes in heat. The change in heat triggers seismic waves, resulting in an earthquake.

3. Explosion Earthquakes

These are caused by nuclear explosions. They are, essentially, man triggered kind of earthquakes and represent the biggest impact of modern-day nuclear war. During the 1930s nuclear tests conducted by the United States, numerous small towns and villages were devastated as a result of this grave act.

4. Collapse Earthquakes

These kinds of earthquakes are generally smaller and most commonly occur near underground mines. They are sometimes referred to as mine bursts. Collapse earthquakes are instigated by the pressure generated within the rocks. This kind of earthquake leads to the collapse of the roof of the mine instigating more tremors. Collapse earthquakes are prevalent in small towns where underground mines are located.

Seismograph of earthquakes

The seismograph is a device that detects and draws the vibrations of the ground and is based on the operation of a simple pendulum. A seismograph's oscillation frequency depends on the **pendulum's resonance frequency. T**he length of the pendulum axis determines the type of seismograph and earthquakes to be measured, and the formula for obtaining the period of an oscillation is as follows:

$$T = 2\pi\sqrt{\frac{L}{g}}$$

where:

- T: is the period of the pendulum expressed in seconds;
- L: is the length of the wire that supports the mass;
- g: is the value of the acceleration of gravity, and on Earth, it is equal to 9.81 m / s ^{2}.

Richter scale (M_L)

A Richter scale is a quantitative measure of an earthquake's magnitude (size), was devised in 1935 by American seismologists Charles F. Richter and Beno Gutenberg.

The earthquake's magnitude is determined using the logarithm of the amplitude (height) of the largest seismic wave calibrated to a scale by a seismograph.

On the original Richter scale, the smallest earthquakes measurable at that time were assigned values close to zero on the seismograph of the period.

Since modern seismographs can detect seismic waves even smaller than those originally chosen for zero magnitudes, it is possible to measure earthquakes having negative magnitudes on the Richter scale.

Each increase of one unit on the scale represents a 10-fold increase in the magnitude of an earthquake. In other words, numbers on the Richter scale are proportional to the common (base 10) logarithms of maximum wave amplitudes.

Each increase of one unit also represents the release of about 31 times more energy, which is represented by the previous whole number on the scale. (That is, an earthquake measuring 5.0 releases 31 times more energy than an earthquake measuring 4.0.)

Tsunami

The word 'Tsunami' literally means "harbor wave."

A tsunami is a catastrophic ocean wave, usually caused by a submarine earthquake, an underwater or coastal landslide, or a volcanic eruption. Waves radiate outward from the generating impulse at speeds of up to 500 miles (800 km) per hour, reaching maximum heights of 100 feet (30 meters) near coastal areas

Characteristics of tsunami

*Tsunamis are among Earth's most infrequent hazards and most of them are small and nondestructive.

*Over deep water, the tsunami has very long wavelengths. When a tsunami enters shallow water, its wavelength gets reduced and the period remains unchanged, which increases the wave height.

*Tsunamis have a small amplitude (wave height) offshore. This can range from a few centimetres to over 30 m in height. However, most tsunamis have less than 3 m wave height. *It radiates in all directions from the point of origin and covers the entire ocean.

*It generally consists of a series of waves, with periods ranging from minutes to hours. These are the waves generated by tremors and not by earthquakes themselves.

*There is no season for tsunamis and not all tsunamis act the same. It cannot be predicted where, when, and how destructive it will be. A small tsunami in one place may be very large a few miles away.

*An individual tsunami may impact coasts differently. A tsunami can strike any ocean coast at any time. They pose a major threat to coastal communities. The effect of a Tsunami would occur only if the epicenter of the tremor is below oceanic waters and the magnitude is sufficiently high.

*The speed of the wave in the ocean depends upon the depth of the water. It is more in the shallow water than in ocean deep.

How are tsunamis generated?

A tsunami can be generated only through the vertical movement of the seafloor. Most tsunamis are generated by earthquakes. Volcanic eruption, underwater explosion, landslides, and meteorite impacts are some other causes of tsunamis.

Causes

The details of the causes of the tsunami is explained below:

Earthquake – Tsunami is generated by the earthquake because of the disturbance of the seafloor and is formed generally with vertical displacement. Most tsunamis are generated by earthquakes that occur along the subduction boundaries of plates along the ocean trenches. The size of a tsunami is related to the size of the earthquake.

Underwater explosion – A nuclear testing by the US generated a tsunami in 1940 and 1950s in Marshall Island.

Volcanic eruption – Volcanoes that occur along the coastal waters can cause several effects that can cause a tsunami.

Landslides – Earthquakes and volcanic eruptions generally generate landslides, these landslides when moving into the oceans, bays, and lakes can generate tsunamis.

Meteorite Impacts – Though no historic example as such of meteorite impact has caused tsunamis, the apparent impact of a meteorite about 5 million years ago produced tsunamis leaving deposits along the Gulf Coast of Mexico and the United States.

Engineering measures

1) Through the development and installation of enormous building shock absorbers, sliding walls, and Teflon foundation pads, these structures are able to help Japanese buildings withstand the immense stresses and strains imposed on them during violent events like earthquakes.

2)Another part of Japan's engineering solutions revolves around the construction of massive sea walls -- sometimes up to around 40 feet (12 meters) tall. Such enormous structures are designed to help protect highly populated areas.

3)Other engineering solutions include the design and construction of monstrous floodgates that are intended to channel, tamper, or redirect incoming tsunami waves away from critical infrastructure and population centers. These can be absolutely huge, up to 51 feet (15.5 meters) tall.

Landslides

A landslide is the movement of rock, earth, or debris down a sloped section of land. Landslides are caused by rain, earthquakes, volcanoes, or other factors that make the slope unstable.

Landslides have three major causes, namely, geology, morphology, and human activity.

*Geology refers to characteristics of the material itself. The earth or rock might be weak or fractured, or different layers may have different strengths and stiffness.

*Morphology refers to the structure of the land. For example, slopes that lose their vegetation to fire or drought are more vulnerable to landslides. Vegetation holds soil in place, and without the root systems of trees, bushes, and other plants, the land is more likely to slide away. A classic morphological cause of landslides is erosion, or weakening of earth due to water.

Types of landslides

Falls Landslides: It means falling of some material or debris or rocks etc., from a slope or a cliff which leads to a collection of this debris at the base of the slope.

Topple Landslides: These can occur because of some fractures between the rocks and the tilt of the rocks because of gravity without collapsing. Here, we see the forward rotational movement of the material.

Slides: It is a kind of landslide when a piece of the rock slides downwards and gets separated from it.

Spread: It happens on flat terrain and gentle slopes and can occur because of softer material

Causes of landslides

Landslides are caused by various factors, which are mentioned below:

*It can be caused because of heavy rain.

*Deforestation is also one of the main reasons for landslides because trees, plants, etc., keep the soil particles compact and due to deforestation, the mountain slopes lose their protective layers because of which the water of the rain flows with unimpeded speed on these slopes.

*It can be caused by earthquakes as well.

Effects

Short Term Impacts

*The natural beauty of the area is damaged.

*Loss of life and property

*Roadblocks

*Destruction of railway lines

*Channel blocking because of the falling of rocks.

*It leads to the diversion of river water, which can cause floods as well.

Long Term Impacts

*Landscape changes can be permanent.

*The loss of fertile land or cultivation land.

*Erosion and soil loss can lead to environmental problems.

*Population shifting and migration.

*Effects on the sources of water.

*Some roads can be damaged or closed permanently.

Prevention and Mitigation

The following measures can be taken in this regard:

*Early warning systems and monitoring systems should be there.

*Hazard mapping can be done to identify the areas which are more prone to landslides.

*Restriction on the construction in the risky areas should be imposed.

*Afforestation programs should take place.

*Restricting development in landslide areas and protecting the existing ones.

*The country should specify codes or standards etc. For the construction of the buildings and other purposes in such areas of risk.

*Insurance facilities should be taken by the people to deal with the loss.

*Terrace farming should be adopted in hilly areas.

*Response teams should be quick to deal with landslides if they occur.

Forest fires

Forest fires can be defined as any uncontrolled and non-prescribed combustion or burning of plants in a natural setting such as a forest, grassland, bushland, or tundra, which consumes natural fuels and spreads based on environmental conditions.

Methodology

Frequency ratio model and its application

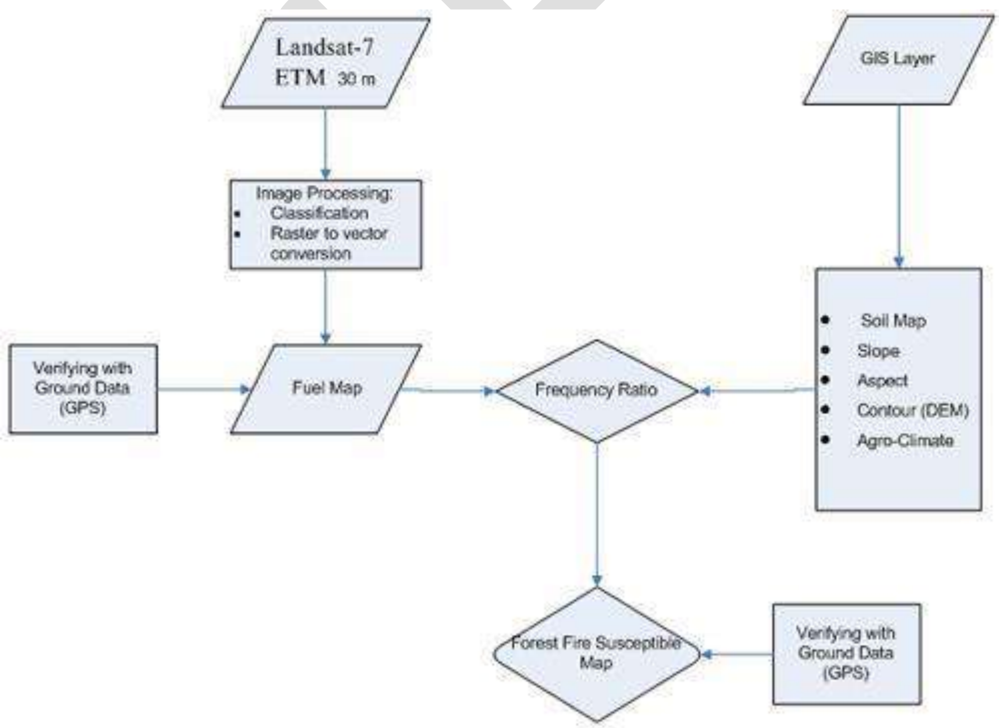
Frequency ratio approaches are based on the observed relationships between the distribution of hotspot and each hotspot-related factor, to reveal the correlation between hotspot locations and the factors in the study area. Using the frequency ratio model, the spatial relationships between hotspot-occurrence location and each factor contributing to hotspot occurrence were derived. The frequency is calculated from an analysis of the relation between the hotspot and the attributing factors. In the relation analysis, the ratio is that of the area where hotspots occurred to the total area so a value of 1 is an average value. If the value is greater than 1, it means a higher correlation and a value lower than 1 means a lower correlation.

To calculate the Forest Fire Susceptibility Index (FFSI), each factor's frequency ratio values were summed to the training area as in equation (1). The hotspot susceptibility value represents the relative susceptible to forest fire occurrence. So the greater the value, the higher the susceptible to forest fire occurrence and the lower the value, the lower the susceptible to forest fire occurrence.

$$FFSI = Fr_1 + Fr_2 + \ldots\ldots + Fr_n \qquad (1)$$

(FFSI: Forest Fire Susceptibility Index; Fr: Rating of each factors' type or range). The forest fire susceptibility map was made using the FFSI values and for interpretation is shown in the figure.

This study consists of development of Forest Fire Susceptible Map. The figure shows the flowchart of the methodology.



Fire

A fire occurs when the elements i.e. heat, fuel, oxygen and chemical chain reaction are present and combined in the right mixture. A fire can be prevented or extinguished by removing any one of the elements in the fire tetrahedron. Essentially all four elements must be present for fire to occur, heat, fuel oxygen, and a chemical chain reaction.

Sources of fire hazards

Fuels include solids, liquids, vapors, and gases. Solid fuels wood, fabrics, synthetic materials, packing materials, papers, etc.

Liquid fuels flammable liquids (e.g., nitro phenol, ammonium nitrate, and potassium chlorate, paint and oil-soaked rags, cotton or cellulose soaked with sulphuric acid, etc.,.).Other sources include flame, sparks, spontaneous ignition, and self-combustible chemicals. (Khanna, 1992).

Prevention of fire hazards

*Well-planned design and layout

*Properly ventilated systems

*Chemical data sheets

*Proper training of personnel

*Proper maintenance of surroundings

*Use of fire extinguishers, alarms, sensors, detectors

*Firefighting equipment

*Sprinkler systems

Fireproofing

Fireproofing is a method of applying certain products over the materials or structures which minimize the escalation of fire and thus plant operators get sufficient to act against the fire.

Typically, fireproofing is designed to protect the structural steel which supports high-risk or valuable equipment.

The failure point is generally considered to be 1000°F, as this is the point where steel has lost approximately 50% of its structural strength.

The aim then is to prevent structural steel from reaching 1000°F for some period of time. Tanks, pressure vessels, and heat exchangers may experience a significant cooling effect from liquid contents and so, less fireproofing protection is generally required.

Some thermal insulation systems may serve a dual role as fireproofing and this is common with some pressure vessels. Piping may be insulated but it is not generally considered to be fireproofed.

Fire safety regulations

The primary framework for fire safety regulations in India is the **National Building Code of India (NBC)**, published by the Bureau of Indian Standards (BIS). The first edition of the NBC was published in 1970.

The third edition of the NBC was published in 2016.

National Building Code 2016 covers:

- Demarcation of the fire zone
- Restriction on the construction of buildings in each fire zone
- Other restrictions and requirements necessary to minimise danger to life from fire, smoke, fumes or panic
- Classification of buildings: Based on occupancy type, height, and floor area.
- Fire resistance requirements: For structural and non-structural components.
- Means of escape: Stairwells, fire escapes, and emergency exits.
- Fire detection and alarm systems: Types, installation, and maintenance.
- **Firefighting equipment:** Extinguishers, sprinklers, and hydrants.
- Storage and handling of hazardous materials: Regulations for specific materials.
- Emergency preparedness and evacuation plans: Drills, training, and signage.

Overall, the code broadly covers the following areas:

Fire prevention: This covers aspects of fire prevention pertaining to the design and construction of buildings. It also describes the various types of building materials and their fire rating.

Life safety: This covers life safety provisions in the event of a fire and similar emergencies, also addressing construction and occupancy features that are necessary to minimize danger to life from fire, smoke, fumes or panic.

Fire protection: Covers significant appurtenances (accessories) and their related components and guidelines for selecting the correct type of equipment and installations meant for fire protection of the building, depending upon the classifications and type of building.

The guidelines for fire drills and evacuations for high-rise buildings are also specified in NBC Part 4. It mandates the appointment of a qualified fire officer and trained staff for significant land uses.

Questions

1. Discuss the classification of earthquakes.
2. Enumerate the causes and adverse effects of tsunami waves.
3. Calculate the intensity of earthquake of magnitude 6.5 assuming the base intensity as I_0.
4. Define landslide and describe the causes for landslides.
5. Discuss the engineering measures to withstand earthquakes and tsunami waves.
6. The intensity of one earthquake is 100 times the intensity of the other. If the magnitude of the first earthquake is 8.9 estimate the magnitude of the other.
7. Calculate the intensity of earthquake of magnitude 6.5 assuming the base intensity as I_0.
8. Discuss the engineering measures to withstand landslides.
9. Explain fire safety regulations
10. Explain the sources and prevention of fire hazards.

****