1. Details of Module and its structure

Subject Name	Physics
Course Name	Physics 02 (Physics Part 2 ,Class XI)
Module Name/Title	Unit 10, Module 9, Propagation of energy -Wave Motion Chapter 15, -Waves
Module Id	keph_201501_eContent
Pre-requisites	Oscillations, energy of an oscillator, sound waves, longitudinal waves, transverse wave
Objectives	After going through this module, the learners will be able to: • Know the periodicity of the energy of an oscillator • Understand propagation of energy in a medium • Comprehend the salient features of wave motion • Distinguish between mechanical and electromagnetic waves • Describe and differentiate between transverse and longitudinal waves • Calculate speed of a wave
Keywords	Wave motion, Electromagnetic wave, energy of an oscillator, Mechanical waves, longitudinal waves, transverse waves, particle velocity, wave velocity, Factors effecting speed of waves in materials wavelength, frequency of oscillator and frequency of wave

2. Development team

Role	Name	Affiliation
National MOOC Coordinator (NMC)	Prof. Amarendra P. Behera	Central Institute of Educational Technology, NCERT, New Delhi
Course Coordinator / PI	Anuradha Mathur	Central Institute of Educational Technology, NCERT, New Delhi
Subject Matter Expert (SME)	Ramesh Prasad Badoni	GIC Misras Patti Dehradun Uttarakhand
Review Team	Associate Prof. N.K. Sehgal (Retd.) Prof. V. B. Bhatia (Retd.) Prof. B. K. Sharma (Retd.)	Delhi University Delhi University DESM, NCERT, New Delhi

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Oscillations and waves
Chapter 14: oscillations

Periodic motion, time period, frequency, displacement as a function of time , periodic functions Simple harmonic motion (S.H.M) and its equation; phase; oscillations of a loaded spring-restoring force and force constant; energy in S.H.M. Kinetic and potential energies; simple pendulum derivation of expression for its time period.
Free forced and damped oscillations (qualitative ideas only) resonance

Chapter 15: Waves

Wave motion transverse and longitudinal waves, speed of wave motion , displacement, relation for a progressive wave, principle of superposition of waves , reflection of waves, standing waves in strings and organ pipes, fundamental mode and harmonics, beats, Doppler effect

2. MODULE-WISE DISTRIBUTION OF UNIT SYLLABUS 15 MODULES

Module 1	• **Periodic motion** • **Special vocabulary** • **Time period, frequency,** • **Periodically repeating its path** • **Periodically moving back and forth about a point** • **Mechanical and non-mechanical periodic physical quantities**
Module 2	• **Simple harmonic motion** • **Ideal simple harmonic oscillator** • **Amplitude**

	• Comparing periodic motions phase, • Phase difference Out of phase In phase not in phase
Module 3	• Kinematics of an oscillator • Equation of motion • Using a periodic function (sine and cosine functions) • Relating periodic motion of a body revolving in a circular path of fixed radius and an Oscillator in SHM
Module 4	• Using graphs to understand kinematics of SHM • Kinetic energy and potential energy graphs of an oscillator • Understanding the relevance of mean position • Equation of the graph • Reasons why it is parabolic
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Module13	• Standing waves in pipes closed at one end, • Standing waves in pipes open at both ends • Fundamental and overtones • Relation between fundamental mode and overtone

	frequencies • **Harmonics**
Module 14	• **Beats** • **Beat frequency** • **Frequency of beat** • **Application of beats**
Module 15	• **Doppler effect** • **Application of Doppler effect**

MODULE 9

3. WORDS YOU MUST KNOW

Let us remember the words we have been using in our study of this physics course

- Displacement the distance an object has moved from its starting position moves in a particular direction.SI unit: m, this can be zero, positive or negative
- Non mechanical displacement periodically changing electric, magnetic, pressure of gases, currents, voltages are non-mechanical oscillations. They are represented by sin and cosine functions like mechanical displacements

  For a vibration or oscillation, the displacement could ne mechanical, electrical magnetic. Mechanical displacement can be angular or linear.
- Acceleration- time graph: graph showing change in velocity with time , this graph can be obtained from position time graphs
- Instantaneous velocity

  Velocity at any instant of time

$$v = \lim_{\Delta t \to 0} \frac{\Delta x}{\Delta t} = \frac{dx}{dt}$$

- Instantaneous acceleration

  Acceleration at any instant of time

$$a = \lim_{\Delta t \to 0} \frac{\Delta v}{\Delta t} = \frac{dv}{dt} = \frac{d^2x}{dt^2}$$

- kinematics study of motion without considering the cause of motion
  - **Frequency:** The number of vibrations / oscillations in unit time.
  - **Angular frequency:** a measure of the *frequency* of an object varying sinusoidally equal to 2π times the *frequency* in cycles per second and expressed in radians per second.
  - **Oscillation: one complete to and fro motion about the mean position** *Oscillation* refers to any periodic motion of a body moving about the equilibrium position and repeats itself over and over for a period of time.

- **Vibration:** It is a to and fro motion about a mean position. The periodic time is small, so we can say oscillations with small periodic time are called vibrations. The displacement from the mean position is also small.
- **Inertia:** *Inertia* is the tendency of an object in motion to remain in motion, or an object at rest to remain at rest unless acted upon by a force.
- **Sinusoidal:** **like a sin θ $vs\theta$** A sine wave or sinusoid is a curve that describes a smooth periodic oscillation.
- **Simple harmonic motion (SHM):** repetitive movement back and forth about am equilibrium (mean) position, so that the maximum displacement on one side of this position is equal to the maximum displacement on the other side. The time interval of each complete vibration is the same.
- **Harmonic oscillator:** A *harmonic oscillator* is a *physical* system that, when displaced from equilibrium, experiences a restoring force proportional to the displacement.
- **Mechanical energy:** is the sum of potential **energy** and kinetic **energy**. It is the **energy** associated with the motion and position of an object.
- **Restoring force:** is a *force* exerted on a body or a system that tends to move it towards an equilibrium state.
- **Conservative force:** is a *force* with the property that the total work done in moving a particle between two points is independent of the taken path. When an object moves from one location to another, the *force* changes the potential energy of the object by an amount that does not depend on the path taken.
- **Bob:** A *bob* is the weight on the end of a pendulum
- **Periodic motion:** **motion** repeated in equal intervals of time.
- Simple pendulum: If a heavy point-mass is suspended by a *weightless*, inextensible and perfectly flexible string from a rigid support, then this arrangement is called a 'simple pendulum'

- Restoring Force: No net force acts upon a vibrating particle in its equilibrium position. Hence, the particle can remain at rest in the equilibrium position. When it is displaced from its equilibrium position, then a periodic force acts upon it which is always directed towards the equilibrium position. This is called the 'restoring force'. The spring gets stretched and, due to elasticity, exerts a restoring force F on the body directed towards its original position. By Hooke's law, the force F is given by

$$F = -kx,$$

Displacement Equation of SHM:

$$y = a \sin \omega t$$

Time period: The time taken by an oscillating system to complete one oscillation,

$$T = 2\pi/\omega.$$

Frequency: The number of oscillations in one second is called the 'frequency' (n) of oscillation system.

$$n = \frac{1}{T} = \frac{\omega}{2\pi}$$

Phase: When a particle vibrates, its position and direction of motion vary with time. The general equation of displacement is

$$y = a\sin(\omega t + \phi),$$

ϕ is called the 'initial phase' we usually we have $\phi = 0$ when we are talking about the SHM of a single particle.

Velocity in SHM: v in terms of **a** and $\boldsymbol{y}$ as

$$v = \omega\sqrt{a^2 - y^2}$$

Acceleration in SHM: Acceleration of a moving particle is

$\therefore\ \alpha = -\left(\frac{v^2}{a^2}\right)y.$ or $\alpha = -\omega^2 y.$

Displacement Equation of SHM in terms of cos:

You have learned already the SHM in earlier module. There you must have used the expression for displacement as

$$x = a\cos\omega t$$

The velocity equation is $v = -a\,\omega\sin\omega\,t$

The acceleration equation is $\alpha = -a\,\omega^2\cos\omega\,t = -\omega^2 x.$

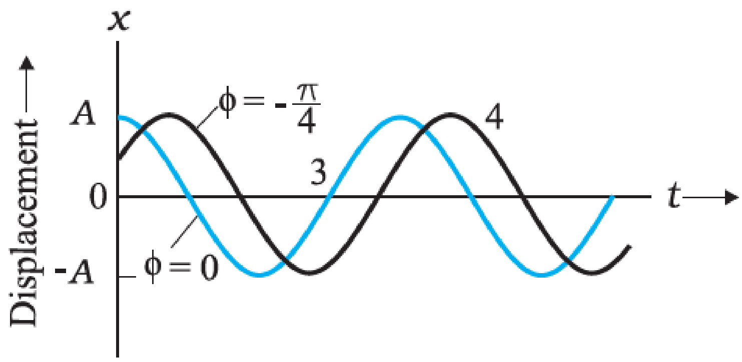
The displacement may be written as,

$x = a\cos(\omega t + \emptyset),$ where $\emptyset$ is the initial phase

Displacement-Time Graph in SHM

$$\mathbf{x(t) = A\cos(\omega t + \emptyset)}$$

.



A plot obtained from Eq. The curves 3 and 4 are for $\emptyset = 0$ and $\emptyset = \frac{\pi}{4}$ respectively. The amplitude A is same for both the plots

4. INTRODUCTION:

We studied the motion of objects oscillating in isolation. What happens in a system, which is a collection of such objects?

A material medium provides such an example.

Here, elastic forces bind the constituents to each other and, therefore, the motion of one affects that of the other.
If you drop a little pebble in a pond of still water, the water surface gets disturbed. The disturbance does not remain confined to one place, but propagates outward along a circle.

http://www.markjp.com/work/

If you continue dropping pebbles in the pond/ tub of water, you see circles rapidly moving outward from the point where the water surface is disturbed by the pebble.

It **gives a feeling** as if the water is moving **outward from the point of disturbance**. If you put a small paper boat on the disturbed surface, it is seen that the boat move up and down but does not move away from the centre of disturbance.

This shows that the water mass does not flow outward with the circles, but rather a moving disturbance is created.

Similarly, when we speak, the sound moves outward from us, without any flow of air from one part of the medium to another. The **disturbances** produced in air are much less obvious and only our ears or a microphone can detect them.

These patterns of energy , which move without the actual physical transfer or flow of matter as a whole, are called waves.

We will study waves in this module.

WAVES

Waves transport energy and the pattern of disturbance has information that propagates from one point to another.

All our communications essentially depend on transmission of signals through waves.

Speech means production of sound waves in air and hearing means their detection.

Often, communication involves different kinds of waves. For example, sound waves may be first converted into an electric current signal which in turn may generate an electromagnetic wave that may be transmitted by an optical cable or via a satellite. Detection of the original signal will usually involve these steps in reverse order.

Not all waves require a medium for their propagation.

We know that light waves can travel through vacuum. The light emitted by stars, which are hundreds of light years away, reaches us through inter-stellar space, which is practically a vacuum.

The most familiar type of waves such as waves on a string, water waves, sound waves, seismic waves, etc. is the so-called mechanical waves.

These waves

- **They require a medium for propagation,**
- **They cannot propagate through vacuum.**
- **They involve oscillations of constituent particles and**
- **The speed of propagation of energy depend on the elastic properties of the medium.**

The electromagnetic waves that you will learn in Class XII are a different type of wave.

- **Electromagnetic waves do not necessarily require a medium –**
- **They can travel through vacuum.**
- **Light, radio waves, X-rays, are all electromagnetic waves.**
- **In vacuum, all electromagnetic waves have the same speed c, whose value is 3×10^8 m/s. the highest speed known to man as of today.**

5. ENERGY OF AN OSCILLATOR

Let us recall, our considerations for a simple harmonic motion.

Here we described the oscillations or vibrations of a particle or a system which executed to and fro motion about a mean position, for which the acceleration was always directed towards the mean position

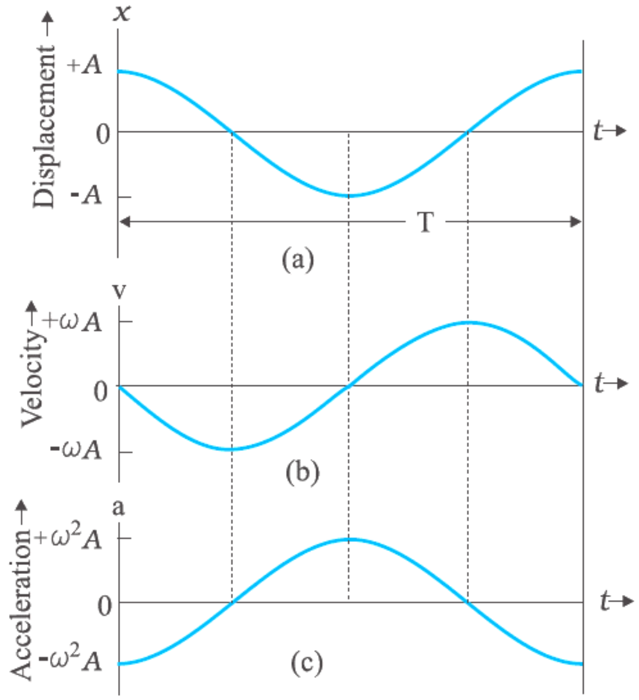
The displacement, velocity and acceleration varied periodically we could express the equations of motion by

Displacement $x = A\cos\omega t$

Velocity $v = -A\,\omega\sin\omega\,t$

Acceleration $\alpha = -A\,\omega^2\cos\omega\,t = -\,\omega^2 x$

And the corresponding graphs as



Displacement, velocity and acceleration of a particle in simple harmonic motion have the same period T, but they differ in phase

The particle executes SHM when some external force is used to cause a displacement. The additional potential energy gained by the system causes it to execute SHM.

During oscillations the energy is conserved, and an ideal oscillator will continue to oscillate forever.

The energy oscillates between kinetic energy and potential energy for a mechanical oscillation.

The sum of potential energy and kinetic energy of an oscillating source remain constant or the Total Energy of a Body in SHM is always constant. When a body oscillates in simple harmonic motion, it is acted upon by a (restoring) force which tends to bring it back to the equilibrium position. The restoring force is proportional to the displacement and its direction is opposite to that of displacement. Due to this force, there is potential energy in the body. Also, as the body is in motion, it has kinetic energy.

During a mechanical oscillation of the body, the two mechanical energies convert into each other, but their sum remains constant, assuming that friction is negligible.

We explain these energies.

Potential Energy (U) Let m be the mass of the oscillating body and y its displacement from the equilibrium position at an instant t. Then, the displacement equation of SHM will be

$$y = a \sin \omega t$$

where a is amplitude of oscillation of the body and ω is the angular velocity of the body.

The *linear velocity of the body*

$$v = \frac{dy}{dt} = a\omega \cos \omega t = \omega\sqrt{a^2 - y^2}$$

And linear acceleration of the body

$$\alpha = \frac{dv}{dt} = -a\,\omega^2 \sin \omega t = -\omega^2 y$$

The restoring force acting on the body at this instant is given by

$$F = mass \times acceleration$$

$$= m\,\alpha = -m\,\omega^2 y$$

If the body undergoes a further infinitesimally small displacement dy, **the work done against the restoring force** is given by

$$d\,W = (-F)dy = m\,\omega^2\,y\,dy$$

The **total work done** for displacing the body through y can be obtained by intergrating the R.H.S. of the above equation between the limits $y = 0$ to $y = y$, that is,

$$W = \int_0^y m\,\omega^2\,y\,dy = m\,\omega^2 \left[\frac{y^2}{2}\right]_0^y = \frac{1}{2}\,m\,\omega^2\,y^2$$

This **work done on the body** appears as **potential energy(U) of the body at that instant. Thus,**

$$U = \frac{1}{2}\,m\,\omega^2 y^2$$

Clearly, the potential energy U of the body increases with increase of displacement y and in the extreme position of oscillation of the body ($where$ $y = A$) is maximum.

Kinetic Energy (K): When the displacement of a body in SHM is y, its velocity is given by

$v = \omega\sqrt{A^2 - y^2}$, where A is the amplitude of motion.

Hence, the instantaneous kinetic energy of the body is

$$K = \frac{1}{2}\,m\,v^2 = \frac{1}{2}\,m\,\omega^2(A^2 - y^2)$$

Clearly, **the kinetic energy K of the body decreases with increase of displacement y and in the equilibrium position (where $y = 0$), it is maximum.**

Total Energy: On adding kinetic energy and potential energy, the total energy of the body is given by

$$E = U + K$$

$$= \frac{1}{2} m\,\omega^2\;y^2 + \frac{1}{2} m\,\omega^2\;(A^2 - y^2) = \frac{1}{2} m\,\omega^2 A^2$$

It is evident from this that the total energy of the body is independent of displacement y, that is, it remains same during the motion of the body.

In the **position of maximum displacement** ($\boldsymbol{when\;\; y\; = A}$) the total energy is in the form of potential energy, while in the equilibrium position ($when\; y = 0$) the total energy is in the form of kinetic energy. This can be seen by putting $y = aA$

$U = \frac{1}{2}\,\mathrm{m}\,\omega^2 \mathrm{y}^2 \;= \frac{1}{2}\,\mathrm{m}\,\omega^2 \mathrm{A}^2$

And $\boldsymbol{y = 0}$

$\mathrm{K} = \frac{1}{2}\,\mathrm{m}\,\omega^2(\mathrm{A}^2 - \mathrm{y}^2) = \frac{1}{2}\,\mathrm{m}\,\omega^2 \mathrm{A}^2$

In other positions, both forms of the energy exist.

We know that $\omega\;= 2\,\pi f$, where f is the frequency. Hence,

$$\boxed{\boldsymbol{E = \frac{1}{2}\,\mathrm{m}\,\omega^2 \mathrm{A} = 2\pi^2\,\mathrm{m}\;\mathrm{f}^2\,\mathrm{A}^2}}$$

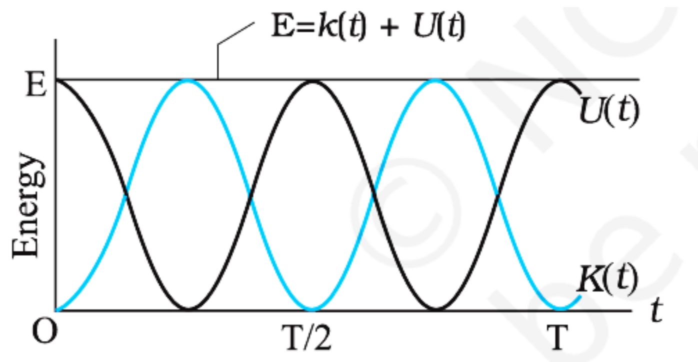
Thus, in SHM, the total energy of a particle is directly proportional to the square of the amplitude (A^2) and to the square of the frequency(f^2).

IMPORTANT POINTS ABOUT ENERGY:

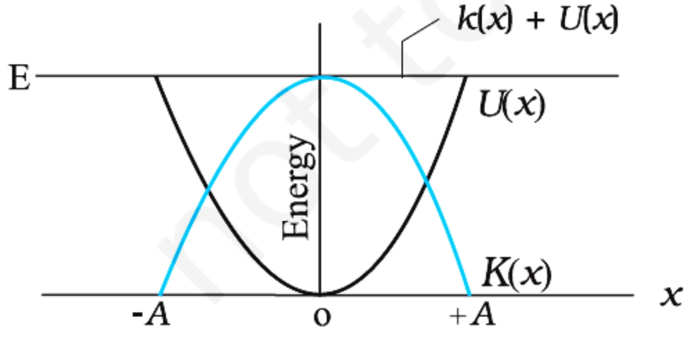
a) In equilibrium position $y = 0$, we have
Potential energy of the body $U = 0(zero)$
And kinetic energy of the body $K = \frac{1}{2} m\,\omega^2\;A^2 = E\;(maximum)$

b) In maximum displace position $y = A$, we have
Potential energy of the body $U\; = \frac{1}{2} m\,\omega^2\;A^2 = E\;(maximum)$

And kinetic energy of the body $K = O(zero)$



(a)



(b)

Kinetic energy, potential energy and total energy as a function of time [shown in (a)] and displacement [shown in (b)] of a particle in SHM. The kinetic energy and potential energy both repeat after a period T/2. The total energy remains constant at all t or x.

Corresponding to certain values of displacement y, the values of U, K and E is shown in the Table.

Corresponding to these values, graphs of potential energy, kinetic energy and total energy are shown in Fig.

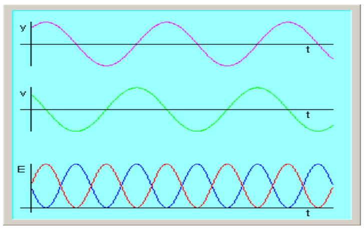
Displacement (y)	$y = 0$	$y = \frac{a}{2}$	$y = \frac{a}{\sqrt{2}}$	$y = \frac{a\sqrt{3}}{2}$	$y = a$
Potential energy (U)	0	$\frac{E}{4}$	$\frac{E}{2}$	$\frac{3E}{4}$	E
Kinetic energy (K)	E	$\frac{3E}{4}$	$\frac{E}{2}$	$\frac{E}{4}$	0
Total energy	E	E	E	E	E

Graphs of potential energy and kinetic energy are parabolas and graph of total energy is a straight line- graph (b)

Time-Energy Graph-graph (a)

In simple harmonic motion, let

Displacement $y = \sin \omega t$, and $velocity,\ v = \frac{dy}{dt} = a\,\omega \cos \omega t$



Hence, potential energy

$$U = \frac{1}{2} m\omega^2 y^2 = \frac{1}{2} m\,\omega^2\, a^2 sin^2\, \omega t$$

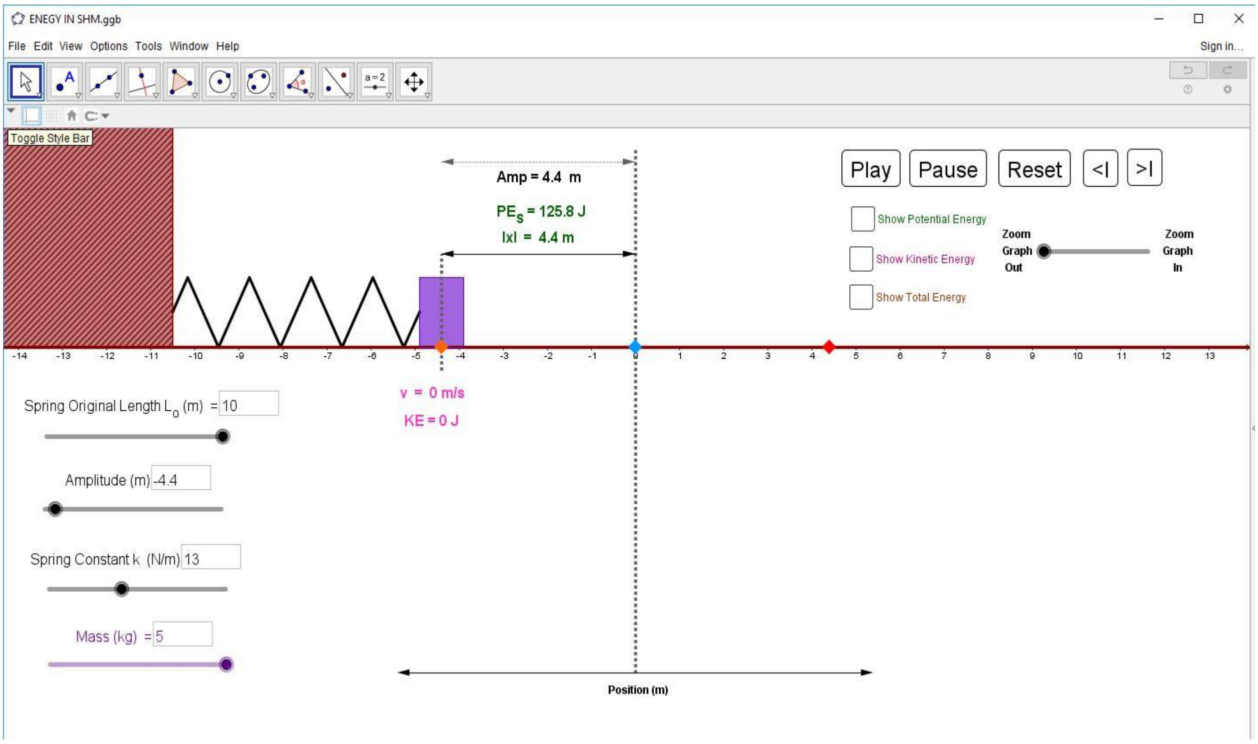
Kinetic energy

$$K = \frac{1}{2} m\, v^2 = \frac{1}{2} m\omega^2 a^2\, cos^2\, \omega t$$

Total energy $E = K + U = \frac{1}{2} m\,\omega^2\, a^2$

It is clear from both eq. that potential energy *(U)* and kinetic energy *(K)* change periodically with time while total energy *(E)* remains constant. These graphs with time are shown in Fig. It is clear from these graphs that in one time-period of SHM two vibrations of potential energy *(U)* and kinetic energy *(K)* are completed. Hence, the frequency of changing potential energy *(U)* and kinetic energy *(K)* with time is twice the frequency of simple harmonic motion.

ENEGY IN SHM ggb



Source: Geogebra

6. OSCILLATING SOURCE AND PROPAGATION OF ENERGY

Waves in elastic media are intimately connected with harmonic oscillations. (Stretched strings, coiled springs, air, etc., are examples of elastic media).

We shall illustrate this connection through simple examples.

Consider a collection of springs connected to one another as shown in Fig.

If the **spring at one end** is pulled suddenly and released, the disturbance travels to the other end. What has happened? The first spring is disturbed from its equilibrium length. Since the **second spring is connected** to the first, it is also stretched or compressed, and so on. **The disturbance** moves from one end to the other; but each spring only executes small oscillations about its equilibrium position.

As a practical example of this situation, consider a stationary train at a railway station.

Different bogies of the train are coupled to each other through a spring coupling. When an engine is attached at one end, it gives a push to the bogie next to it; this push is transmitted from one bogie to another without the entire train being bodily displaced.

Now let us consider the propagation of sound waves in air. As the wave passes through air, it compresses or expands a small region of air. This causes a change in the density of that region, say δd, this change induces a change in pressure, δp, in that region. Pressure is force per unit area, so there is a **restoring force proportional** to the disturbance, just like in a spring.

In this case, the quantity similar to **extension or compression** of the **spring is the change in density.**

If a **region is compressed, the molecules in that region are packed together, and they tend to move out to the adjoining region, thereby increasing the density or creating compression in the adjoining region.**

Consequently, the air in the first region undergoes **rarefaction**. If a region is comparatively rarefied the surrounding air will rush in making the rarefaction move to the adjoining region.

Thus, the compression or rarefaction moves from one region to another, making the propagation of a disturbance possible in air.

A collection of springs connected to each other. The end A is pulled suddenly generating a disturbance, which then propagates to the other end.

So, if an oscillating system is placed in an elastic medium. It becomes a source of energy, causing the neighboring particles, also to be set into oscillation.

The medium particles will have amplitude according to the amount of energy of the source

The frequency of vibration of medium particles will necessarily be the same as the source.

In **solids,** similar arguments can be made. In a **crystalline solid, atoms or group of atoms are arranged in a periodic lattice**.

In these, each atom or group of atoms is in equilibrium, due to forces from the surrounding atoms.
Displacing one atom, keeping the others fixed, leads to restoring forces, exactly as in a spring.
So we can think of atoms in a lattice as end points, with springs between pairs of them.

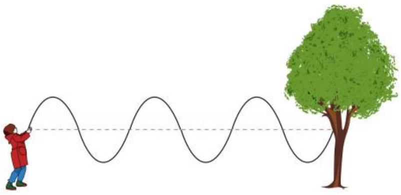
We are going to discuss various characteristic properties of waves

7. WAVES AND WAVE MOTION

When we throw a stone in the calm water of a pond, we see that a disturbance is produced at the place where the stone strikes the water. This disturbance advances outward in the same form and reaches the edges of the pond as shown in fig.

After some time the disturbance is no longer there and the pond surface acquires a non-disturbed look. The sudden travel of energy through a medium is called **pulse.**

In the same way, if we tie one end of a rope to a tree and move the other end up and down, then a type of disturbance is produced in the rope which advances with a definite speed (shown in fig.). Such a disturbance is called a 'mechanical wave'.



Source: Wikimedia

In the above example, when the **stone falls in the water, the water particles at that place start moving up and down**.
These particles pass over their motion to the neighboring particles and come back to their original positions.
The neighboring particles, in turn, hand over their motion to their next particles and this process continues.
It is clear that in this process, the water particles do not leave their positions permanently; they simply oscillate up and down about their mean positions while the disturbance produced by the stone is continuously transmitted through water.
We can see this also by placing a cork on the water surface. The disturbance causes the cork to move up and down at its place and the disturbance goes on advancing.

Similarly, if we mark the rope at any point with a ribbon tied tightly and then produce disturbance at its end, we see that the **mark moves up and down at the same place while the disturbance proceeds ahead**.
Thus, the mechanical waves transmit energy and momentum through the limited motion of the particles of the material medium, while the particles remain in their positions.

In other words, mechanical waves transmit energy and momentum, while the particles do not move from their position.
This transmission is possible because of the two properties of the medium:

- The elasticity and inertia.

Water-waves, sound-waves, waves in a spring, etc., are examples of mechanical waves.

8. ELECTROMAGNETIC WAVES

You would study these in course physics 03
Since all wave propagation properties are the same we are including a brief description here.

Electromagnetic waves propagate through space carrying radiant energy.

For example; **radio waves, microwaves, infrared, (visible)light, ultraviolet, X and gamma radiation. Electromagnetic radiation consists of electromagnetic waves.**

These are synchronized oscillations of electric and magnetic fields that propagate at the speed of light through vacuum.

The oscillations of EM fields are perpendicular to each other in a plane which is perpendicular to the direction of propagation of the wave. The EM wave is transverse in nature. It is produced by moving charged particle and it carries energy and momentum which it imparts to matter when it interacts with it.

Source: Wikipedia

DIFFERENCE BETWEEN MECHANICAL AND ELECTROMAGNETIC WAVES

MECHANICAL WAVES	ELECTROMAGNETIC WAVES
Necessarily requires a medium for their propagation	It doesn’t need any medium to travel or can propagate through vacuum also
Particles of the medium perform SHM about their mean position	Oscillating electric and magnetic fields perpendicular to each other and perpendicular to the direction of propagation
These are elastic waves	These are due to variation of EM fields

Its typical speed is that of sound 330 m/s in air	Its speed is 3×10^8 m/s in air or vacuum
They can be Transverse, longitudinal, and surface waves.	These are transverse in nature

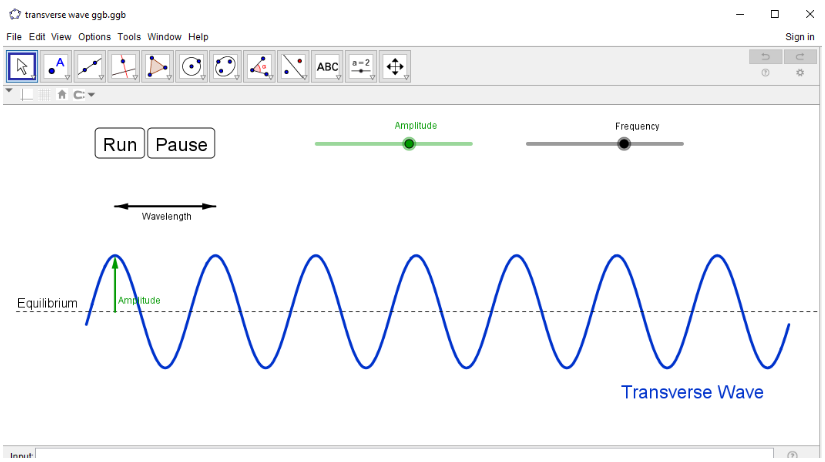
Video clip: **https://youtu.be/SNUNohhpwQs**

9. TRANSVERSE AND LONGITUDINAL WAVES

When a progressive mechanical wave propagates in a medium; the particles of the medium are set in oscillation.

Depending upon the direction of oscillation of these particles, the waves have been classified as of two types: transverse waves and longitudinal waves.

Transverse wave ggb.ggb

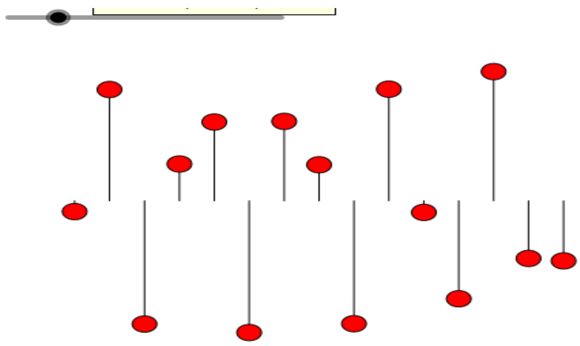


Source: Wikimedia

TRANSVERSE WAVES:

If on propagation of a mechanical wave through a medium, the medium particles oscillate along a **direction perpendicular to the direction of propagation of the wave, the wave is called a 'transverse' wave.**

For example, when one end of a horizontal rope is tied to a hook and the other end is moved up and down or sideways, then waves are propagated in the rope along its length.
If there is a mark on the rope, then this mark is seen to oscillate perpendicular to the direction of propagation of the wave. Hence, the waves in the rope are transverse. Light (electromagnetic) waves are also transverse.
Pendulum wave .ggb
Transverse and longitudinal wave .ggb



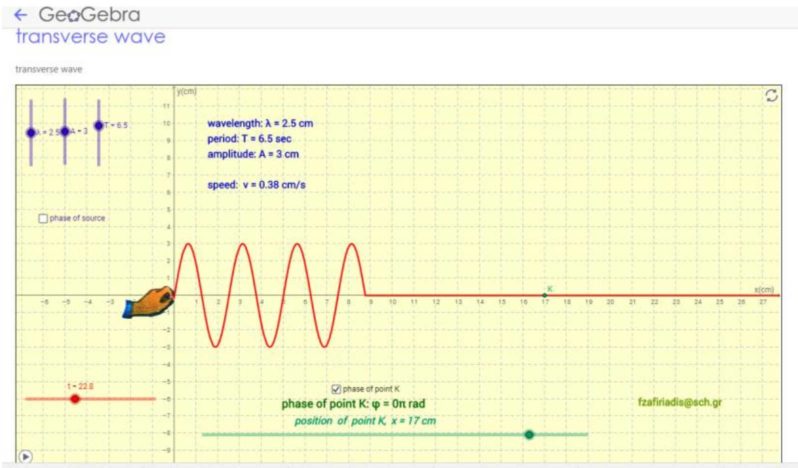
Source: Geogebra

In a transverse wave, the position of maximum displacement in the upward direction is called 'crest' and the position of maximum displacement in the downward direction is called 'trough',

These states of crest and trough continue to advance in the direction of motion of the wave.

The distance between two successive crests, or between two successive troughs, is called the **'wavelength' of the transverse wave.**

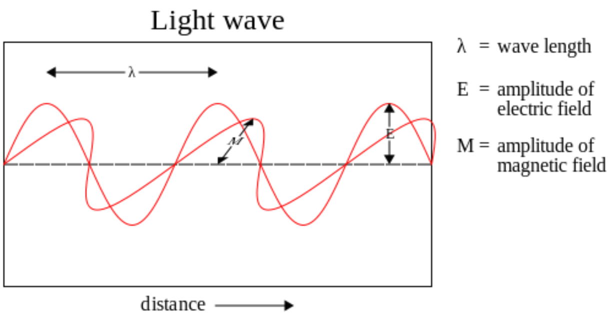
Transverse wave -ggb.JPG



Source: Geogebra

Mechanical transverse waves can be produced only in solids which have rigidity.

Hence, transverse waves cannot be produced in gases. In liquids, transverse waves cannot be formed in the interior; they can be formed only on surfaces of liquids.

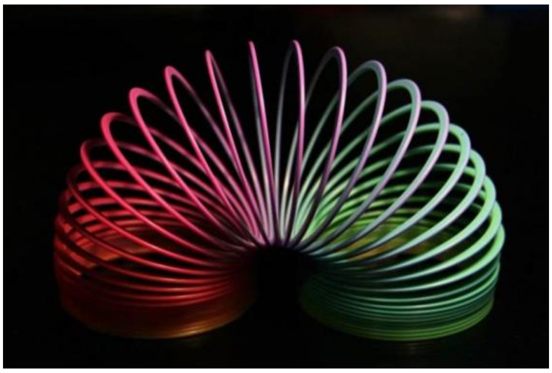


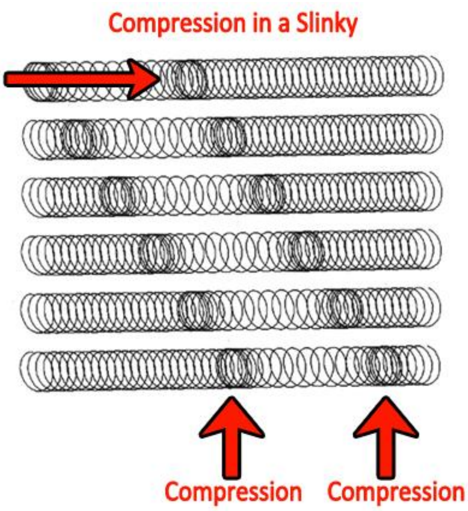
Source: Wikipedia

LONGITUDINAL WAVES:

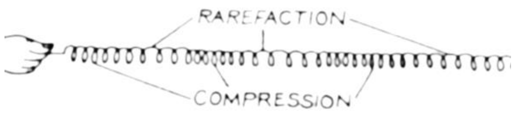
If on propagation of **a mechanical wave through a medium, the medium particles oscillate parallel to the direction of propagation of the wave**, **the wave is called a 'longitudinal' wave**.

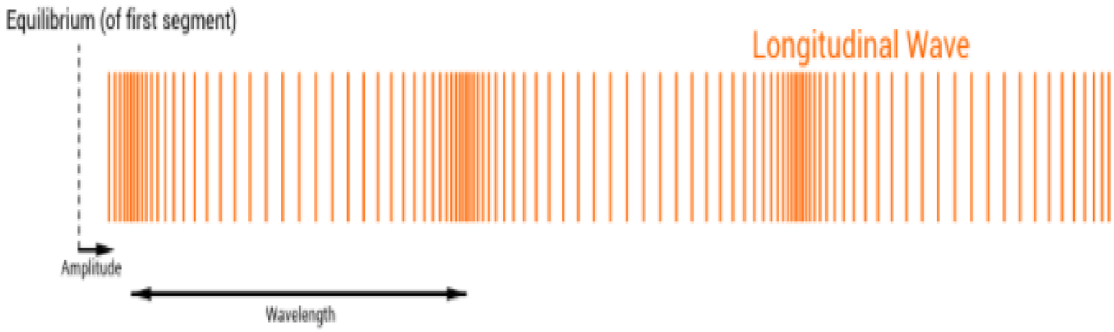
For example, when one end of a long spring (slinky) is tied to a hook in a wall and the other end is moved forward and backward, then every turn of the spring oscillates parallel to the length of the spring and longitudinal waves propagate through the spring.





If **we observe the whole spring placed horizontally,** and give it a jerk (send a pulse through it) at some places the turns of the spring are seen to be closer and at some other places they are seen to be farther than in the normal state of the spring.





Geogebra

The places where the **turns are closer are said to be in the state of 'compression'** while the places where the **turns are farther said to be in the state of 'rarefaction'**.
These states of compression and rarefaction continue to advance in the direction of the length of the spring.
The distance between two successive compressions, or between two successive rarefactions, is called the 'wavelength' of the longitudinal wave.

Longitudinal waves can be produced in all types of media (solid, liquid and gases).

The **mechanical waves produced in air are always longitudinal**. The waves produced in the interior of liquids are longitudinal, although transverse waves are possible on the surface of liquids.

During the propagation of longitudinal waves in a medium, the **density and pressure** of the medium at the **places of compression are greater than in the normal state of the medium (because there the particles of the medium are closer than in normal state);** while the density and pressure at the places of rarefaction are smaller than in normal state (because there the particles are farther than in normal state.

Wave motion is a method of energy transfer in which the particles of the medium do not leave their position but execute SHM in their positions, but the energy is transferred from the source to any observer.

EXAMPLE

Given below are some examples of wave motion. State in each case if the wave motion is transverse, longitudinal or a combination of both:

a. Motion of a kink in a longitudinal spring produced by displacing one end of the spring sideways.

b. Waves produced in a cylinder containing a liquid by moving its piston back and forth.

c. Waves produced by a motorboat sailing in water.

d. Ultrasonic waves in air produced by a vibrating quartz crystal.

SOLUTION

a. Transverse and longitudinal
b. Longitudinal
c. Transverse and longitudinal
d. Longitudinal

RELATION BETWEEN FREQUENCY, WAVE SPEED AND WAVE LENGTH:

Let f **be the frequency and** T **the time-period of an oscillating source body**.

The wave produced by this body will travel a distance λ in one time period. Thus,

$$\text{Distance travelled in } T \text{ seconds} = \lambda$$

$$\therefore \text{Distance travelled in 1 second} = \frac{\lambda}{T}$$

But, the distance travelled in 1 second is the **speed** v **of the wave**.

Therefore,

$$\mathbf{v} = \frac{\boldsymbol{\lambda}}{\mathbf{T}}$$

$$[\because \; f = 1/T]$$

$$\mathbf{v} = \mathbf{f}\,\boldsymbol{\lambda}$$

Speed = frequency × wavelength.

10. SPEED OF WAVES

The speed with which a disturbance travels in a medium is called speed of waves. Since different mediums will respond differently to the same source, let us see the factors which affect the speed of waves in a medium

Speed of Transverse Waves

Transverse waves are possible only in solids, because solids have rigidity. The speed of a transverse wave in a solid is given by the following relation

.

$$\mathbf{v} = \sqrt{\frac{\eta}{d}}$$

where η is modulus of rigidity of the material of the solid and d is its density.

The speed of transverse wave in a flexible stretched string depends upon the **tension in the string and the mass per unit length of the string**.
Mathematically, the speed v is given by

$$\mathbf{v} = \sqrt{\frac{T}{m}}$$

where **T is the tension in the string and m is the mass per unit length of the string (not the mass of the whole string)**.

If r be the radius of the string and d the density of the material of the string, then

m = volume per unit length × density

$$= \pi r^2 \times 1 \times d = \pi r^2 d$$

Then, the speed of transverse wave is

$$v = \sqrt{\frac{T}{\pi r^2 d}}$$

But, $$\frac{T}{\pi r^2} = \frac{\text{Tension in the string}}{\text{area of cross-section}} = \text{stress}$$

∴ Speed of **transverse wave in the string,**

$$\mathbf{v} = \sqrt{\frac{\text{stress}}{\text{denstiy}}}$$

Speed of longitudinal waves

Longitudinal waves can travel in all the three types of media; solid, liquid and gas. The speed of a longitudinal wave in a medium depends only upon the properties of the medium; not upon the amplitude or shape of the wave. The properties of the medium controlling the speed of the wave are ‘elasticity’ and ‘inertia’.

Speed of longitudinal Waves in Solids: The speed of longitudinal waves in an extended solid is given by

$$\mathbf{v} = \sqrt{\frac{B + (4/3)\,\eta}{d}}$$

where **B, η and d are the bulk modulus, modulus of rigidity and density of the material of the solid respectively.**

If the solid is in the form of a long rod, then the speed of longitudinal waves in the rod is given by

$$\mathbf{v} = \sqrt{\frac{\mathbf{Y}}{\mathbf{d}}}$$

Where **Y is Young's modulus of the material of the solid and d is density.**

EXAMPLE,

For iron $Y = 2.0 \times 10^{11} Nm^{-2}$ and $d = 7.7 \times 10^{3}$ kg m^{-3}. Calculate the speed of sound waves in iron

SOLUTION

The speed of longitudinal waves in an iron rod is

$$\mathbf{v} = \sqrt{\frac{\mathbf{Y}}{\mathbf{d}}}$$

$$v = \sqrt{\frac{2.0 \times 10^{11}}{7.7 \times 10^{3}}} = 5096\ m\ s^{-1}$$

Sound waves are longitudinal waves; the speed of sound in iron is nearly 5130 m s^{-1}.

This value, within the experimental limits, is sufficiently near the value obtained by the above formula.

Speed of Longitudinal Waves in Liquids: The speed of longitudinal waves in liquids is given by

$$\mathbf{v} = \sqrt{\frac{\mathbf{B}}{\mathbf{d}}}$$

Where B is bulk modulus of the liquid and d is density

EXAMPLE

Calculate the speed of sound in water if, bulk modulus of water, $B = 2.0 \times 10^{9}\ Nm^{-2}$ and density is $d = 1.0 \times 10^{3}\ kg\ m^{-3}$.

SOLUTION

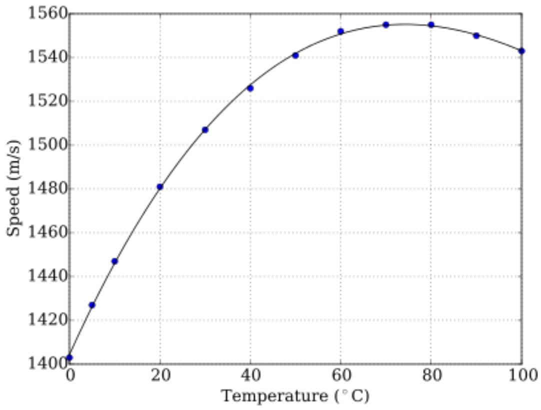
$$v = \sqrt{\frac{B}{d}}$$

Therefore, the speed of longitudinal waves in water is

$$v = \sqrt{\frac{2.0 \times 10^{9}}{1.0 \times 10^{3}}} = \mathbf{1414\ m\ s^{-1}}$$

By experiment, the speed of sound (longitudinal waves) in water is 1450 ms^{-1}.

This is also in accordance with the formula.



Source: *Wikipedia*

Speed of Longitudinal Waves (or Sound) in Gases: Newton's Formula

The formula for the speed of longitudinal waves in gases is the same as for the liquids, that is, the speed of longitudinal waves in gases is given by

$$\mathbf{v} = \sqrt{\frac{\mathbf{B}}{\mathbf{d}}}$$

Where B is coefficient of volume elasticity of the gas and d is density.

Newton was of the opinion that when longitudinal waves (sound) travel in a gas, the temperature of the gas remains constant.

Hence in the above formula,

B is isothermal bulk modulus of the gas whose value is equal to the initial pressure (P) of the gas.

Therefore, according to Newton, the speed of sound in a gas should be obtained by the following formula,

$$\mathbf{v} = \sqrt{\frac{\mathbf{P}}{\mathbf{d}}}$$

Let us use this formula to calculate the speed of sound in air. We know that

Pressure of air (p) at 0° C = 1.01×10^5 N m^{-2} and

Density of air (d) = 1.29 kg m^{-3}.

Hence, the **speed of sound at 0° in air** is

$$v = \sqrt{\frac{1.01 \times 10^5}{1.29}} = \mathbf{280\ m\ s^{-1}},$$

But, experimental results showed, the speed of sound in air at 0° C to be nearly 331m/s which is quite different from the value obtained by Newton's formula. Hence, Newton's formula for gases was not accepted.

LAPLACE'S CORRECTION:

Laplace discovered the discrepancy in Newton's formula and modified it satisfactorily. In fact, when sound waves travel in a gaseous medium, then at any point in the medium the states of compression and rarefaction occur alternately. At the time of compression some heat is developed at the point and at the time of rarefaction some heat is lost from the medium at that point.

The compressions and rarefactions occur so rapidly that the heat produced during compression cannot escape into the surroundings and the heat lost during rarefaction cannot come in from the surrounding. Besides this, the exchange of heat does not take place because gases are bad conductors of heat.

Hence, the temperature at a point in the medium rises during compression and falls during rarefaction. That is, during propagation of sound waves, adiabatic temperature-changes take place in the gaseous medium.

Hence, in Newton's formula, B should represent the **adiabatic bulk modulus of the gas whose value is equal to $\gamma \times P$, where**

$$\gamma = \frac{C_p}{C_V}$$

$$= \frac{specific\ heat\ of\ gas\ at\ constant\ pressure}{specific\ heat\ gas\ at\ constant\ volume}$$

Thus, according to ***Laplace, the formula for the speed of sound in a gas is***

$$\mathbf{v} = \sqrt{\frac{\gamma P}{d}}$$

For **monoatomic gases** (**such as helium, argon, neon, etc**.) the value of γ **is 5/3**=1.67

For **diatomic gases** (**such as oxygen, nitrogen, hydrogen,** etc.) the value of γ **is 7/5** = 1.41.

Air **contains mainly nitrogen and oxygen** and so the value of γ **for air is 1.41**.

Hence, according to Laplace, the speed of sound in air at 0° C is

$$\mathbf{v} = \sqrt{1.41} \times 280\ \mathrm{ms^{-1}} = 332\ \mathrm{ms^{-1}}$$

This **value agrees closely with the experimental value. Hence, Laplace modified formula is correct.**

It is clear from the above description that the speed of sound is different in different media. The speed of sound is minimum in gases, more in liquids, and maximum in solids.

11. EFFECT OF PRESSURE, TEMPERATURE AND HUMIDITY ON SPEED OF SOUND WAVES IN GASES

Effect of Pressure:

From the formula for the speed of sound in a gas, $v = \sqrt{\gamma P/d}$, it appears that the speed of sound (v) should change when the pressure (P) changes. But, actually it is not so. Let 1 gram-molecule (mole) of a gas have a pressure P and a volume V. If T be the absolute temperature of the gas, then according to the gas equation,

$$PV = RT,$$

where R is the universal gas constant. If the molecular-weight of the gas (that is, mass of 1 mole of the gas) be M and density be d, then $V = M/d$, and we have

$$P(M/d) = RT$$

$$\frac{P}{d} = \frac{RT}{M} = constant, \qquad \text{(If T is constant)}$$

That is, **at constant temperature, if *P* changes then d also changes in such a way that the ratio *P/d* remains constant**.

Hence, **in the expression $\mathbf{v = \sqrt{\gamma\, P/d}}$,**

the value of P/d does not change when P changes.

From this, it is clear that **if the temperature of the gas remains constant, then there is no effect of the pressure change on the speed of sound.**

Effect of Temperature:

For a gas the value of the ratio, P/d depends upon the temperature of the gas.

If we heat a gas, there are **two** possibilities.

- If the **gas is free to expand**, then on being heated it would expand; its density (d) would decrease while its pressure (P) should remain the same. Thus, the value of the ratio P/d will increase.
- If the **gas is closed in a vessel**, then on being heated, its pressure will increase while the density will not change. Again the value of the ratio p/d will increase. Hence in both conditions, the speed of sound will increase with increase in temperature of the gas. Since

$$\frac{\mathrm{P}}{\mathrm{d}} = \frac{\mathrm{R\,T}}{\mathrm{M}},$$

Where *M* is the molecular-weight of the gas and *T* is the absolute temperature, the speed of sound in the gas is

$$v = \sqrt{\frac{\gamma\, P}{d}}$$

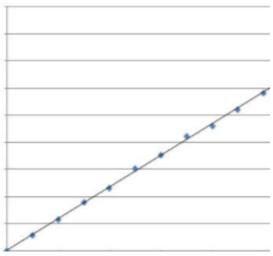
Putting the above value of *P/d*, we get

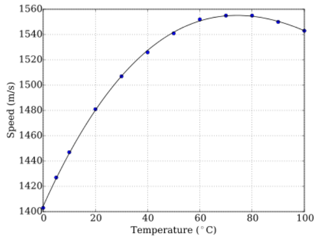
$$v = \sqrt{\frac{\gamma R T}{M}}$$

Thus $v \propto \sqrt{T}$

It is evident from this that **the speed of sound in a gas is directly proportional to the square-root of its absolute temperature.**

If we draw a graph between v^2 and T then it will be a straight line and a graph between v and T then it will be a parabola as shown here.





Source-Wikipedia

Now,

if v_0 be the speed at 0 °C and v_t the speed at t °C, then from the above equation, we have

$$v_0 = \sqrt{\frac{\gamma R}{M}} \times \sqrt{0 + 273}$$

And $$v_t = \sqrt{\frac{\gamma R}{M}} \times \sqrt{t + 273}$$

Dividing v_t by v_0, we get

$$\frac{v_t}{v_0} = \sqrt{\frac{t + 273}{273}} = \sqrt{\frac{273+t}{273}} = \sqrt{1 + \frac{t}{273}}\ 0$$

$$\therefore v_t = v_0 \left(1 + \frac{t}{273}\right)^{1/2} = v_0 \left(1 + \frac{1}{2} \times \frac{t}{273}\right)$$ (By binomial theorem)

Or $$v_t = v_0 \left(1 + \frac{t}{546}\right)$$

If the speed of sound in air at $0\,^{\circ}C$, v_0 be taken 332 ms^{-1}, then

$$v_t = 332\, ms^{-1} \left(1 + \frac{t}{546}\right)$$

$$\mathbf{v_t = (332 + 0.61\, t)\, m\, s^{-1}.}$$

Thus, the

velocity of sound in air increases roughly by 0.61 ms^{-1} per degree Celsius rise in temperature.

Effect of Humidity:

The **density of moist air (that is, air mixed with water-vapor) is less than the density of dry air.** Therefore,

assuming the value of γ for moist air same as for dry air, it is clear from the formula

$$v = \sqrt{\gamma P/d}$$

that the **speed of sound in moist air is slightly greater than in dry air.**

Effect of Frequency:

There is no effect of frequency of sound on velocity of sound. Sound waves of different frequencies travel with the same speed in air although their wavelengths in air are different. If the speed of sound were dependent on the frequency, the various frequencies in an orchestra will reach at different times and because of the distortion, we would not be able to enjoy the orchestra.

Speed of Sound in Different Gases

If the value of γ for any two gases be the same, the speed of sound in them be v_1 and v_2 at the same temperature and pressure would be, when densities of the gases be $d_1$and d_2

$$v_1 = \sqrt{\gamma P/d_1} \text{ and } v_2 = \sqrt{\gamma P/d_2}\,.$$

$$\frac{v_1}{v_2} = \sqrt{\frac{d_2}{d_1}}.$$

If the **molecular masses of the gasses be *M₁* and *M₂*** respectively, then

$$v_1 = \sqrt{\frac{\gamma R T}{M_1}} \text{ and } v_2 = \sqrt{\frac{\gamma R T}{M_2}} \text{ as derived above}$$

$$\frac{v_1}{v_2} = \sqrt{\frac{M_2}{M_1}}$$

Thus, t**he speed of sound in a gas is inversely proportional to the square- root of the density or the molecular mass of the gas.**

EXAMPLE

Molecular masses of H_2 and O_2 are 2 and 32 respectively.

a) Show that the speed of sound in the two gases is different

b) In which gas would the speed be higher?

c) Find the ratio of speeds in the two gases.

SOLUTION

a) The velocity is inversely proportional to the molecular mass

$$v_1 = \sqrt{\frac{\gamma R T}{M_1}}$$

b) Molecular mass of oxygen is greater hence speed will be lesser in it as compared to hydrogen

c)

$$\frac{\boldsymbol{Vo_2}}{\boldsymbol{V_H}} = \sqrt{\frac{\boldsymbol{M_H}}{\boldsymbol{Mo_2}}}$$

If at any temperature speed of sound in these gases be V_{0x} and V_H, then

$$\frac{\boldsymbol{Vo_2}}{\boldsymbol{V_H}} = \sqrt{\frac{\boldsymbol{M_H}}{\boldsymbol{Mo_2}}} = \sqrt{\frac{2}{32}} = \frac{1}{4}$$

Hence, at the **same temperature, the speed of sound in oxygen is one-fourth the speed of sound in hydrogen.**

TRY THESE

- **A stone dropped from the top of a tower of height 300 m high splashes into the water of a pond near the base of the tower. When is the splash heard at the top given that the speed of sound in air is 340 m s $^{-1}$? (g = 9.8 m s^{-2})**

- **A steel wire has a length of 12.0 m and a mass of 2.10 kg. What should be the tension in the wire so that speed of a transverse wave on the wire equals the speed of sound in dry air at 20 °C = 343 m s^{-1}?**

- **Use the formula**

$$v = \sqrt{\frac{\gamma P}{\rho}}$$

to explain why the speed of sound in air

  a. **is independent of pressure,**
  b. **increases with temperature,**
  c. **increases with humidity.**

- **A hospital uses an ultrasonic scanner to locate tumours in a tissue. What is the wavelength of sound in the tissue in which the speed of sound is 1.7 km s^{-1}? The operating frequency of the scanner is 4.2 M Hz.**

12. SUMMARY

- Any mechanical oscillating source gives out energy

- The energy is transmitted by method of oscillation of particles of the medium which should have inertia and elasticity.
- The particles of the medium do not travel but the energy travels from one particle to its adjacent particle due to elasticity.
- **Wave Speed:** The distance traversed by a wave in 1 second is called the 'wave speed'. It is denoted by v.

- Mechanical waves can exist in material media and are governed by Newton's Laws.
- Transverse waves are waves in which the particles of the medium oscillate perpendicular to the direction of wave propagation.
- *Longitudinal waves* are waves in which the particles of the medium oscillate along the direction of wave propagation.
- *Progressive wave* is a wave that moves from one point of medium to another.
- *Wavelength* of a progressive wave is the distance between two consecutive points of the same phase at a given time. In a stationary wave, it is twice the distance between two consecutive nodes or antinodes.
- *Period T* of oscillation of a wave is defined as the time any element of the medium takes to move through one complete oscillation.
- *Frequency ν* of a wave is the frequency of the source
- *Speed* of a progressive wave is given by

$$\mathrm{v} = \sqrt{\frac{\text{Elasticity}}{\text{density}}}$$

- *The speed of a transverse wave* on a stretched string is set by the properties of the string. The speed on a string with tension *T* and linear mass density is

$$\mathbf{v} = \sqrt{\frac{\mathbf{T}}{\mathbf{m}}}$$

Sound waves are longitudinal mechanical waves that can travel through solids, liquids, or gases.

$$v = \sqrt{\frac{\gamma P}{\rho}}$$