

CHAPTER

6

Sound

From our earliest years, we become

accustomed to a great variety of sounds : our mother's voice, a telephone ringing, a kitten purring, a piano being played, a siren, a jet engine roaring, a rifle shot. Some of these sounds are pleasant to the ear and some are not. Sounds are a form of energy produced by rapidly vibrating objects. We hear sounds because this energy stimulates the auditory nerve in the human ear.

In the 18th century, philosophers and scientists debated the question, "If a tree falls in the forest and no one is there to hear it, will there be sound?" "Of course there will," said the scientists, "because the crash of the tree is a vibrating source that sends out sound waves through the ground and the air." To them, sound was the motion of the particles in a medium caused by a vibrating object.

"Of course not," said the philosophers, "because no observer is present." To them, sound was a personal sensation that existed only in the mind of the observer. This debate could never be resolved because one group was defining sound objectively in terms of its cause, and the other was defining it subjectively in terms of its effects on the human ear and brain. In physics, we study the transmission of sound objectively, leaving the subjective interpretation of the effects of sound waves on the human ear and brain to the philosophers.

The ears of most young people respond to sound frequencies of between 20 Hz and 20 000 Hz. Frequencies of less than 20 Hz are referred to as **infrasonic** and those higher than 20 000 Hz are called **ultrasonic**.

6.1

The speed of sound

Sound seems to move very quickly. However, during a thunderstorm, you see the lightning before you hear the thunder it causes. Light travels extremely fast (3.0×10^8 m/s in vacuum or air); sound travels much more slowly. Accurate measurements of the speed of sound in air have been made at various temperatures and air pressures. At normal atmospheric pressure and 0°C, the speed of sound in air is 332 m/s. If the air pressure remains constant, the speed of sound increases as the temperature increases. For every rise in temperature of 1°C, the speed of sound in air increases by 0.59 m/s. The speed of sound in air at normal atmospheric pressure can be calculated using the equation,

$$v = v_0 \left(1 + \frac{t}{273} \right)^{1/2} \quad \text{Where, } v_0 = \text{speed of sound at } 0^\circ\text{C} = 332 \text{ m/s ; } t \text{ is temperature in } ^\circ\text{C}.$$

For $t \ll 273^\circ\text{C}$, an approximate formula is,

$$v = (332 + 0.6 t) \text{ m/s}$$

- If the temperature drops below 0°C, the speed of sound in air is less than 332 m/s.

NUMERICAL CHALLENGE 6.1

Calculate the speed of sound in air when the temperature is 16°C.

Solution

Give, $t = 16^\circ\text{C}$ $v = ?$

$$\begin{aligned}
 v &= (332 + 0.6 t) \text{ m/s} \\
 &= (332 + 0.6 \times 16) \text{ m/s} \\
 &= \mathbf{341.6 \text{ m/s}}
 \end{aligned}$$

Speed of sound in different media

Speed of sound is different in different media. Sound waves can travel through solids, liquids and gases. The speed of sound is fastest in solids, faster in liquids, and slowest in gases. Speed of sound waves depends on the nature of material (or medium). As a sound wave travels through a material, the particles in the material collide with each other. In a solid, molecules are closer together than in liquids or gases, so collisions between molecules occur more rapidly than in liquids or gases. Thus, the speed of sound is fastest in solids, where molecules are closest together, and slowest in gases, where molecules are farthest apart.

Factors affecting speed of sound

- (1) **Effect of density** : Higher the density, lesser will be the velocity and vice-versa.

$$v \propto \sqrt{\frac{1}{\rho}} \quad \text{Also, } \frac{v_2}{v_1} = \sqrt{\frac{\rho_1}{\rho_2}}$$

For example, under similar condition, $v_{H_2} > v_{O_2}$. This is because $\rho_{H_2} < \rho_{O_2}$.

- (2) **Effect of humidity** : Density of water vapours is less than dry air at same pressure and temperature. Thus, density of moist air is less than that of dry air.

$$\text{Now, } v \propto \sqrt{\frac{1}{\rho}}$$

Therefore, speed of sound increases as humidity increases.

- (3) **Effect of temperature** : As the temperature increases, speed of sound increases and vice-versa.

Since, $v \propto \sqrt{T}$ Where. T is temperature in Kelvin.

$$\text{Also, } \frac{v_1}{v_2} = \sqrt{\frac{T_1}{T_2}}$$

- (4) **Effect of pressure** : There is no effect on the speed of sound by changing the pressure. It is true in every case whether the temperature is constant or not.
- (5) **Effect of wind** : If wind speed and speed of sound are in same directions, they are added together i.e., speed of sound increases. If wind speed and speed of sound are in opposite directions, the net speed of sound is the difference of them i.e., speed of sound decreases.

NUMERICAL CHALLENGE 6.2

1. A pistol is used at the starting line to begin a 500 m race along a straight track. At the finish line, a puff of smoke is seen and 1.5 s later the sound is heard. What is the speed of the sound ?

Solution

Time taken by the light to reach our eyes is extremely small as it travels very fast thus, we can neglect the time taken by the light to reach our eyes.

Thus, time taken (t) by the sound to reach the observer is 1.5 s. Also, pistol is fired at the finish line, thus, the distance travelled (s) to reach the starting line is 500 m.

$$\text{Now, } v = \frac{\text{distance}}{\text{time taken}} = \frac{s}{t} = \frac{500}{1.5} = 333.3 \text{ m/s}$$

2. A vibrating 400 Hz tuning fork is placed in fresh water. What is the frequency in hertz and the wavelength in metres (a) within the water at 25°C ? (b) when the sound waves move into the air at 25°C ?

Take, speed of sound in water at 25 °C = 1500 m/s and speed of sound in air at 25 °C = 345 m/s.

Solution

- (a) Frequency of any wave does not change with change in medium. Thus, a 400 Hz tuning fork will produce a sound of frequency 400 Hz i.e.,

frequency, $\nu = 400$ Hz

Since, speed of wave changes from one medium to the another, the wavelength of wave also changes from medium to medium.

Given, speed of sound in water, $v = 1500$ m/s

We know that speed of wave = frequency $\times$ wavelength

or $v = \nu \lambda$

$$\text{or wavelength, } \lambda = \frac{v}{\nu} = \frac{1500}{400} = 3.75 \text{ m}$$

- (b) Frequency of wave produced, $\nu =$ frequency of tuning fork = 400 Hz

$$\text{wavelength, } \lambda = \frac{v}{\nu} = \frac{345}{400} = 0.8625 \text{ m} \quad (\text{Given, speed of sound in air, } v = 345 \text{ m/s})$$

6.2

The intensity of sound

There is a difference in loudness between a soft whisper and the roar of nearby thunder. However, the loudness of a sound you hear is a subjective evaluation that depends on several factors, including the objective quantity known as **intensity**. Frequency, wavelength, and speed are all properties of sound that can be measured accurately. Sound intensity is more difficult to measure because the amount of energy involved is small in comparison with other forms of energy. For example, the thermal energy equivalent of the sound energy emitted over a 90 minute period by a crowd of 50000 people is only enough to heat one cup of coffee! Sounds audible to humans can vary in intensity from the quietest whisper (10^{-12} W/m²) to a level that is painful to the ear (10 W/m²)—a difference of a factor of 10^{13} .

One unit used to measure the intensity level of sound is the bel (B), named after Alexander Graham Bell. The decibel (dB) is more common than the bel ($1 \text{ dB} = 10^{-1} \text{ B}$). On the decibel scale, 0 dB is the threshold of hearing (10^{-12} W/m²). The scale is not linear, but is a logarithmic scale.

- Every change of 10 units on the decibel scale represents a tenfold effect on the intensity level. For example, a sound 10 times more intense than 0 dB is 10 dB, a sound 100 times more intense than 0 dB is 20 dB, and a sound 1000 times more intense than 0 dB is 30 dB. The level of sound that is painful to the human ear (130 dB) is 10^{13} times more intense than the level at the threshold of hearing. Some common sound intensity levels for are listed in Table 6.1.

Table 6.1 Some common sound intensity levels

S.No.	Source of sound	Loudness (in dB)	Intensity (W/m ²)
1.	Threshold of hearing	0	10^{-12}
2.	Normal breathing	10	$10^1 \times 10^{-12} = 10^{-11}$
3.	Soft whisper (at 5m)	30	$10^3 \times 10^{-12} = 10^{-9}$
4.	Normal conversation	60	$10^6 \times 10^{-12} = 10^{-6}$
5.	Busy traffic	70	$10^7 \times 10^{-12} = 10^{-5}$
6.	Average factory	80	$10^8 \times 10^{-12} = 10^{-4}$
7.	Threshold of pain	130	$10^{13} \times 10^{-12} = 10^1$

- The loudness of the sounds humans perceive relates to the intensity of the sound. However, the two measures are not the same because the human ear does not respond to all frequencies equally. Average human ear is most sensitive to sound frequencies between about 1000 Hz and 5000 Hz. Lower frequencies must have a higher sound level or intensity to be heard. Also, loudness is a measure of the response of the ear to the sound. Intensity is an objective property of the sound wave — in fact, it is related to the square of the wave amplitude, and does not depend on the particular characteristics of a person's ears. Loudness, on the other hand, is a subjective property of the sound that depends on the human ear, the sensitivity of the ear to the frequency of the sound, and the distance from the source of the sound.

Loudness can be considered as the intensity of an audible sound. If there are two sounds of equal intensity, one is audible and another is inaudible, then, our ears will hear the audible sound as a loud sound while the inaudible sound will not be detected by our ears.

NUMERICAL CHALLENGE 6.3

Normal breathing has an intensity level of 10 dB. What would the intensity level be if a sound were

- (a) 10 times more intense ? (b) 100 times more intense ?

Solution

Intensity level in decibel = 10 dB thus, intensity in $\text{W/m}^2 = 10^1 \times 10^{-12} = 10^{-11}$

- (a) If a sound is 10 times more intense, its intensity in $\text{W/m}^2 = 10 \times 10^{-11} = 10^{-10} = 10^2 \times 10^{-12}$

Thus, intensity level in dB = 20

- (b) If a sound is 100 times more intense, its intensity in $\text{W/m}^2 = 100 \times 10^{-11} = 10^{-9} = 10^3 \times 10^{-12}$

Thus, intensity level in dB = 30

- Intensity of sound (or any wave) is proportional to the square of the amplitude of the sound (or wave).

$$I \propto A^2$$

- Loudness or intensity level (β) is measured in decibels (dB)

$$\beta = 10 \log_{10} \left(\frac{I}{I_0} \right)$$

Where, I = intensity of sound ; $I_0 = 10^{-12}$ Watt/ m^2 called threshold of hearing (minimum intensity that is just audible)

- For $I = I_0$, $\beta = 0$. Human ear is sensitive to the sound intensity (loudness) ranging from 0 - 180 dB.

NUMERICAL CHALLENGE 6.4

1. A normal conversation involves sound intensities of about 3.0×10^{-6} W/m^2 . What is the decibel level for this intensity ?

Solution

Given, $I_0 = 10^{-12}$ W/m^2 (the threshold of hearing) ; $I = 3.0 \times 10^{-6}$ W/m^2

$$\text{Intensity level in dB, } \beta = 10 \log_{10} \left(\frac{I}{I_0} \right) = 10 \log_{10} \left(\frac{3 \times 10^{-6}}{10^{-12}} \right) = 10 \log_{10} (3 \times 10^6) = 10 [\log_{10} 3 + \log_{10} 10^6]$$

$$\text{or } \beta = 10 [0.477 + 6 \log_{10} 10] = 10 [0.477 + 6] = 10 (6.477) = \mathbf{64.77 \text{ dB}}$$

2. A bell is rung at a sound intensity of 70 dB. A trumpet is blown at an intensity level that is greater by a factor of 10^3 . What is the intensity level of the trumpet ?

Solution

Given, $\beta = 70$ dB

$$\text{Now, } \beta = 10 \log_{10} \left(\frac{I}{I_0} \right) \quad \text{or} \quad 70 = 10 \log_{10} \left(\frac{I}{I_0} \right) \quad \text{or} \quad 7 = \log_{10} \left(\frac{I}{I_0} \right)$$

$$\text{or } \left(\frac{I}{I_0} \right) = 10^7 \quad \text{or} \quad I = I_0 \times 10^7 = 10^{-12} \times 10^7 = 10^{-5} \text{ W/m}^2$$

Now, intensity level (I') of trumpet is 10^3 times more than the intensity level of bell i.e.,

$$I' = 10^3 \times 10^{-5} = 10^{-2}$$

Now, intensity level of trumpet in dB,

$$\beta' = 10 \log_{10} \left(\frac{I'}{I_0} \right) = 10 \log_{10} \left(\frac{10^{-2}}{10^{-12}} \right) = 10 \log_{10} (10^{10}) = 10 \times 10 \log_{10} 10 = \mathbf{100 \text{ dB}}$$

- Intensity of sound wave varies inversely with the square of the distance from the source ($I \propto 1/r^2$) i.e., as the distance increases the intensity of sound decreases.

$$\frac{I_2}{I_1} = \frac{r_1^2}{r_2^2}$$

NUMERICAL CHALLENGE 6.5

A helicopter hovers overhead during an air show, causing sound waves to emanate uniformly. If the first listener is 700 m away and the second listener is 1000 m away, by how much has the intensity level of the sound decreased when it reaches listener 2 ?

Solution

Let I_1 be the intensity of sound reached at listener 1 and I_2 be the intensity of sound reached at listener 2.
 Given, $r_1 = 700$ m ; $r_2 = 1000$ m.

$$\frac{I_2}{I_1} = \frac{r_1^2}{r_2^2} \quad \text{or} \quad I_2 = \left(\frac{r_1}{r_2}\right)^2 I_1 = \left(\frac{700}{1000}\right)^2 I_1 = 0.49 I_1$$

Thus, the intensity level is almost one half by the time it reaches listener 2.

6.3

The reflection of sound waves

Just as a mirror reflects light, when sound waves radiating out from a source strike a rigid obstacle, the angle of reflection of the sound waves equals the angle of incidence.

Echoes

Echoes are produced when sound is reflected by a hard surface, such as a wall or cliff. An echo can be heard distinctly only if the time interval between the original sound and the reflected sound is greater than 0.1 s. The distance between the observer and the reflecting surface must be greater than 17 m for an echo to be heard (Fig. 1).

■ The echo-sounder is a device that uses sound reflection to measure the depth of the sea. Similar equipment is used in the fishing industry to locate schools of fish. More sophisticated equipment of the same type is used by the armed forces to locate submarines. All such devices are called **SONAR** (SOund NAvigation and Ranging) devices.

Echolocation

Dolphins and orca whales rely on the production and reflection of sound to navigate, communicate, and hunt in dark waters. The location of an object using reflected sound is called **echolocation**. Both animals produce clicks, whistles, and other sounds that vary in intensity, frequency, and pattern. Lower frequency sounds (0.5 – 50 kHz) probably function mainly for social communication, while higher frequencies (40–150 kHz) are probably used for echolocation.

Most bats use echolocation for navigation in the dark and for finding food. The bat can identify an object by the echo and can even tell the size, shape, and texture of a small insect. If the bat detects a prey, it will generally fly toward the source of the echo, continually emitting high frequency pulses until it reaches its target and scoops the insect up into its wing membranes and into its mouth.

Let a person shout loudly and he hears an echo of his sound after a time 't' that is reflected from a wall or hard surface. Let the distance between the source (the person) and the reflecting surface (the wall) be 's' (see fig. 1). Then, the total distance travelled by the sound to reach again to the listener (the person) will be '2s'. Let 'v' be the speed of sound.

$$\text{Now, speed, } v = \frac{\text{total distance travelled}}{\text{time taken}} = \frac{2s}{t}$$

$$\text{or total distance travelled, } 2s = v \times t \quad \text{---- (1)}$$

$$\text{Distance between the source and the listener, } s = \frac{v \times t}{2} \quad \text{---- (2)}$$

Let us take the speed of sound in air to be 344 m/s. The sound must go to the obstacle and reach back the ear of the listener on reflection after 0.1 s i.e., $t = 0.1$ s.

Hence, the total distance covered by the sound from the point of generation to the reflecting surface and back is,

$$2s = v \times t = (344) \times 0.1 = \mathbf{34.4 \text{ m.}}$$

The distance between the observer and the reflecting surface is,

$$s = \frac{v \times t}{2} = \frac{344 \times 0.1}{2} = \mathbf{17.2 \text{ m,}} \text{ for an echo to be heard.}$$

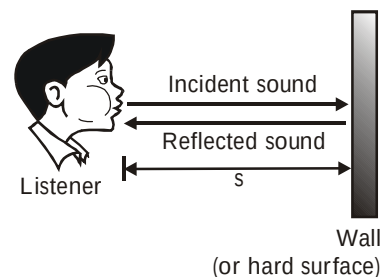


Fig.1 Hearing an echo

NUMERICAL CHALLENGE 6.6

A ship is anchored where the depth of water is 120 m. An ultrasonic signal sent to the bottom of the lake returns in 0.16 s. What is the speed of sound in water ?

Solution

Given, depth of water, $s = 120$ m ; total time of taken by ultrasonic signal, $t = 0.16$ s

$$\text{Speed, } v = \frac{\text{total distance travelled}}{\text{time taken}} = \frac{2s}{t} = \frac{2 \times 120}{0.16} = 1500 \text{ m/s}$$

NUMERICAL CHALLENGE 6.7

1. A boy standing in front of a wall at a distance of 17 m produces 10 claps per second. He notices that the sound of his clapping coincides with the echo. The echo is heard only once when clapping is stopped. Calculate the speed of sound.

Solution

Let s be the distance of wall from the boy. To hear the echo, sound has to travel a total distance $2s$ i.e.,
 total distance travelled by the sound = $2 \times 17 = 34$ m.

Since 10 claps are produced in one second, therefore each clap is produced after $(1/10)s$ which is equal to the time taken for echo to be heard (given in the question that echo coincides with the sound of its clapping) thus,
 $t = (1/10) s$

$$\text{Speed, } v = \frac{\text{total distance travelled}}{\text{time taken}} = \frac{2s}{t} = \frac{2 \times 17}{(1/10)} = 340 \text{ m/s}$$

2. A listener standing between two cliffs fires a gun. He hears the first echo after 1 second and the next after 2 more seconds. Find (a) his distance from the nearer cliff and (b) the distance between the two cliffs.

Take, speed of sound = 330 m/s.

Solution

(a) Let the listener be at a distance s_1 from the nearer cliff 1 and s_2 be his distance from the farther cliff 2 (see fig.2). The first echo will be heard when sound is reflected from the nearer cliff 1. Let t_1 be the time taken by the sound to get back to the listener (i.e., time for first echo). Given, $t_1 = 1$ s

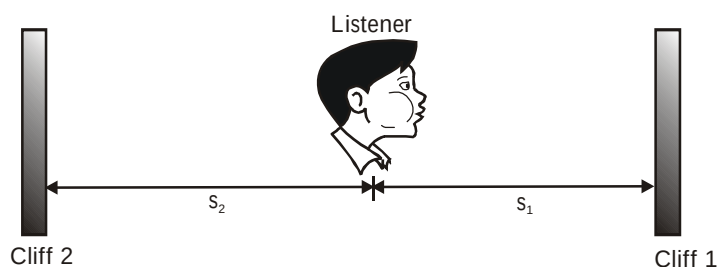


Fig.2 Numerical challenge 6.7 (2)

$$\therefore s_1 = \frac{v \times t}{2} = \frac{330 \times 1}{2} = 165 \text{ m}$$

(b) After the hearing of first echo, second echo is heard after 2 more seconds this means, the time taken t_2 by the sound to get reflected from the farther cliff = $1 \text{ s} + 2 \text{ s} = 3 \text{ s}$ i.e., $t_2 = 3 \text{ s}$.

$$\therefore s_2 = \frac{v \times t}{2} = \frac{330 \times 3}{2} = 495 \text{ m}$$

$$\text{Total distance between the two cliffs} = s_1 + s_2 = 165 + 495 = 660 \text{ m}$$

3. A pilot of an aeroplane travelling horizontally at 198 km/hr fires a gun and hears the echo from the ground after an interval of 3 seconds. If the velocity of sound is 330 m/s, find the height of the aeroplane from the ground.

Solution

Let initially, the aeroplane is at position A when the is gun fired and the pilot hears the echo at position B (see fig.3). The sound first strikes the ground at point G, then reflected and finally reaches at B. Let height, $GP = h$; $AG = GB = x$.

Total distance travelled by sound, $s = AG + GB = x + x = 2x$

$$\text{Speed of sound, } v = \frac{s}{t} = \frac{2x}{t} \text{ or } x = \frac{v \times t}{2} = \frac{330 \times 3}{2} = 495 \text{ m}$$

$$AB = \text{velocity of aeroplane} \times \text{time} = 198 \times \left(\frac{5}{18}\right) \times 3 = 165 \text{ m}$$

$$\text{Now, } AP = AB/2 = 165/2 = 82.5 \text{ m}$$

$$\text{By Pythagorus theorem, } GP = h = \sqrt{AG^2 - AP^2} = \sqrt{(495)^2 - (82.5)^2} = 488 \text{ m}$$

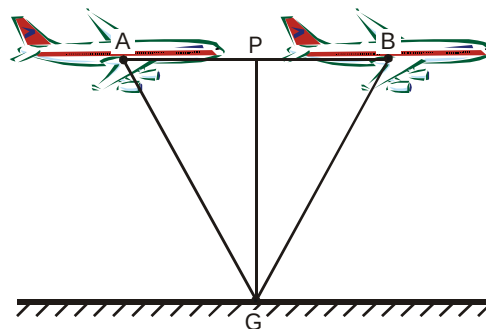


Fig.3 Numerical challenge 6.7 (3)

6.4

Free, damped and forced vibrations

Free vibrations (or free oscillations)

When a body is suspended at one point and if it is displaced slightly from its equilibrium position (or mean position), it starts vibrating or oscillating about its mean position. These are called the free or natural vibrations of the body. The time period of vibration depends on the shape and size i.e., the structure of the body and is called its free or natural period. The frequency of the freely vibrating body is called its natural frequency. Every body has its own natural frequency of vibration.

- The vibrations or oscillations of a body with constant amplitude and constant frequency are called the free vibrations.

Some examples of free vibrations are :

- (1) Motion of the bob of a simple pendulum when it is displaced slightly from its mean position.
- (2) A load suspended from a spring when pulled and released, starts vibrating with a period determined the hardness of the spring and the mass of the load.
- (3) A tuning fork is struck against a hard rubber pad starts vibrating with its natural frequency.
- (4) When we strike the keys of a piano, various strings are set in vibration at their natural frequencies.

Nature of free vibrations : In free vibrations, the restoring force on the vibrating system is directly proportional to its displacement from its mean position. The force is maximum when it is at the extreme ends of vibration and is zero at its mean position. The restoring force is always directed towards the mean position. The amplitude of a freely vibrating body should remain constant. The amplitude will remain constant only if there is no surrounding (resistive) medium. Once a body starts vibrating, it should continue with the same amplitude and same frequency forever. Free vibrations can occur only in vacuum, therefore these vibrations cannot be realised in practice.

Damped vibrations

In most systems, resistive forces, such as friction, air resistance are present and they retard the motion of the system. Consequently, the mechanical energy of the system decreases with time, and such oscillations are called **damped oscillations**.

- The periodic vibrations of decreasing amplitude are called **damped vibrations**.
The damping occurs due to frictional force exerted by the surrounding medium. At any instant the frictional force is proportional to the velocity of the vibrating body. Due to the frictional force, the vibrating system loses energy continuously and hence its amplitude decreases gradually. After some time the total energy of the vibrating system is dissipated to the surroundings and eventually, the vibrating system comes to rest.
- Motion of a simple pendulum in air, vibration of a tuning fork in air, a spring block system oscillating on a rough surface are some examples of damped vibrations.

Forced oscillations

We have seen that the mechanical energy of a damped oscillator decreases with time as a result of the resistive force like friction. It is possible to compensate for this energy decrease by applying an external force that does positive work on the system. Such an oscillator then undergoes **forced oscillations**. At any instant, energy can be transferred into the system by an applied force that acts in the direction of motion of the oscillator. For example, a child on a swing can be kept in motion by appropriately timed “pushes.” The amplitude of motion remains constant if the energy input per cycle of motion exactly equals the decrease in mechanical energy in each cycle that results from resistive forces.

- The vibrations that take place under the influence of an external periodic force are called the **forced vibrations**. When an external periodic force is applied, the body does not vibrate with its own natural frequency, but it gradually acquires the frequency of applied force (driving force). The amplitude of force vibration remains constant with time but its magnitude depends on the frequency of applied force. If the frequency of applied force is quite different from the natural frequency of vibrating body, then the amplitude of vibration is quite small. But if the frequency of the external force is exactly equal to the natural frequency of the vibrating body, the amplitude of vibration is very large.

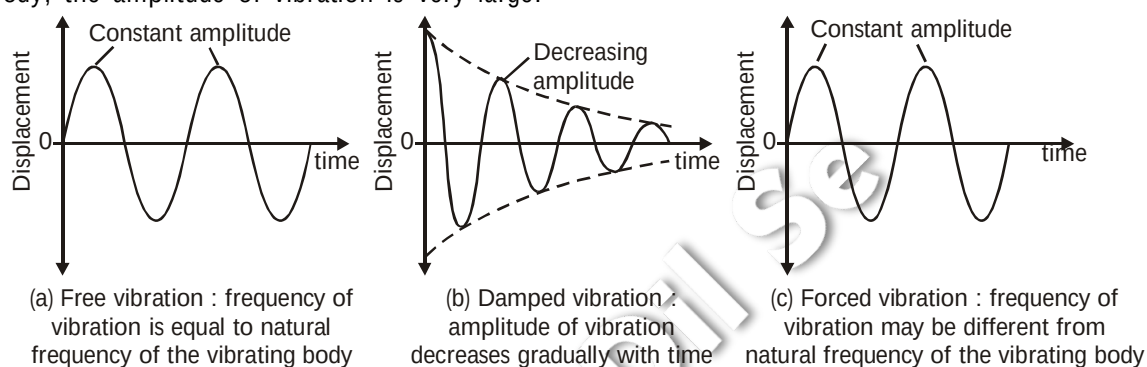


Fig.4 Graphs showing free vibration, damped vibration and force vibration

6.5

Resonance

Every object has a natural frequency at which it will vibrate. To keep a child moving on a swing, we must push the child with the same frequency as the natural frequency of the swing. When a large truck passes your house, you may have noticed that the windows rattle. These are examples of a phenomenon called resonance, which is the response of an object that is free to vibrate to a periodic force with the same frequency as the natural frequency of the object. We also call this phenomenon **mechanical resonance** because there is physical contact between the periodic force and the vibrating object.

- Resonance is a special case of forced oscillations. The phenomenon of dramatic increase in amplitude when the driving force is close to the natural frequency of the oscillator is called **resonance**.
- Resonance can be demonstrated with a series of pendulums suspended from a stretched string (see fig.5). When A is set in vibration, E begins to vibrate in time with it. Although B, C, and D may begin to vibrate, they do not continue to vibrate nor do they vibrate as much. When B is set in vibration, D begins to vibrate in sympathy, but A, C, and E vibrate intermittently and only a little. The pairs A and E, and B and D each have the same lengths and, thus, have the same natural frequencies. They are connected to the same support, so the energy of A, for example, is transferred along the supporting string to E, causing it to vibrate. This occurs only if E is free to vibrate. The periodic vibratory force exerted by one pendulum moves through the supporting string to the other pendulums, but only the pendulum with the same natural frequency begins to vibrate in resonance. When an object vibrates in resonance with another, it is called a **sympathetic vibration**.

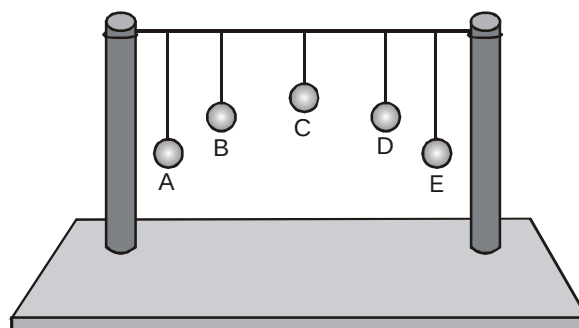
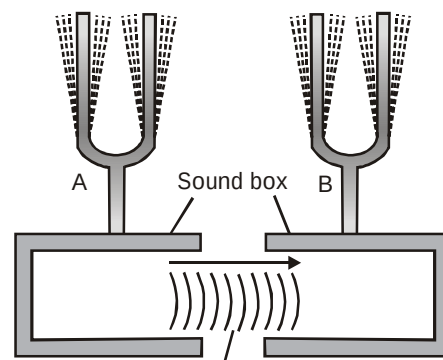


Fig.5 A series of pendulums suspended from a string used to show resonance.

- Another demonstration of resonance can be done by using two identical tuning forks mounted on two separate identical sound boxes (see fig.6). If tuning fork A is set into vibration, the other fork B also starts vibrating and a loud sound is heard. The vibrations produced in second fork B are due to resonance. Vibrating tuning fork A sets the vibrations in the air column of its sound box. These vibrations in the air column of its sound box. These vibrations are communicated to the sound box of the fork B. The air column of sound box of fork B starts vibrating due to resonance. Since the frequency of these vibrations is the same as the natural frequency of the fork B, the fork B also starts vibrating due to resonance.



Sound waves from tuning fork A
Fig.6 Resonance with tuning forks

Applications of resonance

- (1) Mechanical resonance must be taken into account when designing bridges, airplane propellers, helicopter rotor blades, turbines for steam generators and jet engines, plumbing systems, and many other types of equipment. A dangerous resonant condition may result if this is not done. For example, in 1940 the Tacoma Narrows suspension bridge in Washington State collapsed when wind caused the bridge to vibrate. In 1841, a troop of British soldiers marched in step across a bridge, which created a periodic force that set the bridge in resonant vibration and caused the bridge to collapse. If an opera singer sings a note with the same natural frequency as that of a wineglass, the glass will begin to vibrate in resonance. If the sound has a high enough intensity, the wineglass could vibrate with an amplitude large enough that it shatters.
- (2) The human body also has resonant frequencies. Experiments have shown that the entire body has a mechanical resonant frequency of about 6 Hz, of the head between 13 Hz and 20 Hz, and of the eyes between 35 Hz and 75 Hz. Large amplitude vibrations at any of these frequencies could irritate or even damage parts of the body. In transportation and road construction occupations, efforts are made to reduce the effects of mechanical vibrations on the human body.
- (3) Even very large structures, like towers and skyscrapers, can resonate, whether the external source of energy is as small as a gust of wind or as large as an earthquake. Engineers must consider specific structural features to minimize damage by earthquakes.
- (4) Radio and television provide another example of resonance. When you tune a radio or television, you are actually adjusting the frequency of vibration of particles in the receiver so that they resonate with the frequency of a particular signal from a radio or television station.

Stringed instruments

Stringed instruments, like a guitar produce music by making strings vibrate. Different methods are used to make the strings vibrate—guitar strings are plucked, piano strings are struck, and a bow is slid across violin strings. The strings are made of metallic wires.

The pitch (frequency) of the note depends on the length, diameter, and tension of the string. If the string is shorter, narrower, or tighter, the pitch increases. For example, pressing down on a vibrating guitar string shortens its length and produces a note with a higher pitch. Similarly, the thinner guitar strings produce a higher pitch than the thicker strings.

6.6

Mach Number

When aircraft or any object gets close to or goes faster than the speed of sound, a different unit is often used to describe its speed. It's called the **Mach number**, named after Ernst Mach, a prominent physicist from the late 1800s. Mach 1 is defined as the speed of sound at a given air temperature.

The Mach number of a source of sound is the ratio of the speed of the object to the speed of sound in air at that location.

$$\text{Mach number} = \frac{\text{Speed of object}}{\text{Speed of sound}}$$

- If mach number is less than one, this means objects are travelling at speeds less than the speed of sound in air. Such speeds are called have **subsonic** speeds.

If mach number is equal to one, this means objects are travelling at speeds equal to the speed of sound in air. such speeds are called **sonic** speeds. Sonic speed is also called Mach 1.

If mach number is greater than one, this means objects are travelling at speeds more than the speed of sound in air. Such speeds are called **supersonic** speeds. Speeds greater than Mach 1 are supersonic. Speeds for supersonic aircraft, such as the Concorde and fighter aircraft, are given in terms of Mach number rather than km/hr.

NUMERICAL CHALLENGE 6.8

The speed of sound an altitude of 10 km is approximately 1060 km/h. What is the Mach number of an aircraft flying at an altitude of 10 km with a speed of 1800 km/h ?

Solution

$$\text{Mach number} = \frac{\text{Speed of object}}{\text{Speed of sound}} = \frac{1800}{1060} = 1.7$$

The Mach number of an aircraft flying at 1800 km/h at an altitude of 10 km is **1.7**.