Basics of Mechanical Engineering-1

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Week 12

Lecture 49

Vibration and Acoustics

Welcome back to the course Basics of Mechanical Engineering 1. I am teaching this course along with Professor Ramkumar. I am Amandeep. In this course, we are in week 12 and I will discuss Vibration and Acoustics in this lecture. When we talk about vibration analysis or when we talk about acoustics, this is an important topic to be discussed.

We talked about certain failures, we talked about fatigue failure, we talked about the failure examples, the case study which I showed you in the previous lectures. The aircraft body got fractured and the upper part of the fuselage got separated, the bridges collapsed. What was there? In the permanent joints, even leaves of temporary joints because of the vibrations, slowly the fracture could happen or the crack could propagate. Now, in temporary joints, this is very prevalent because of the vibration, the screws get loosened or lot of things could happen like those.

So, vibration analysis is an important topic when we are trying to discuss about the machine elements, when we are trying to discuss about the hardwares in the machine element.

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- Natural Frequency and Resonance
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- Sound Intensity and Pressure
- Acoustics in Mechanical Systems
- Noise Control Techniques
- Vibrations and Noise in Machines
- To Recapitulate

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We will flow this lecture through the Basics of Vibration, Types of Vibrating Systems we will see. We will discuss about Damped and Undamped Vibrations. Then, I will shed some light on Natural Frequency and Resonance. Then, we will talk about Introduction to Acoustics, Sound Intensity and Pressure, we will try to see the relationships between them.

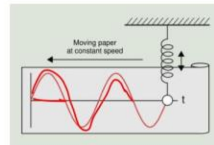
Acoustics in Mechanical Systems, Noise Control Techniques, how could we curb or how could we mitigate the noise. Vibration and Noise in Machines, some examples we will discuss on and I will recapitulate this flow.

Basics of Vibration

What is Vibration?

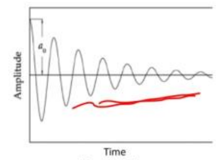
Vibration is the repetitive oscillation of a mechanical system around an equilibrium point.

- It occurs when a system is displaced from its rest position and experiences a restoring force that tries to return it to that position, resulting in a to-and-fro motion.



Types of Vibration:

1. Free Vibration
2. Forced Vibration
3. Damped Vibration
4. Undamped Vibration



Free Vibration

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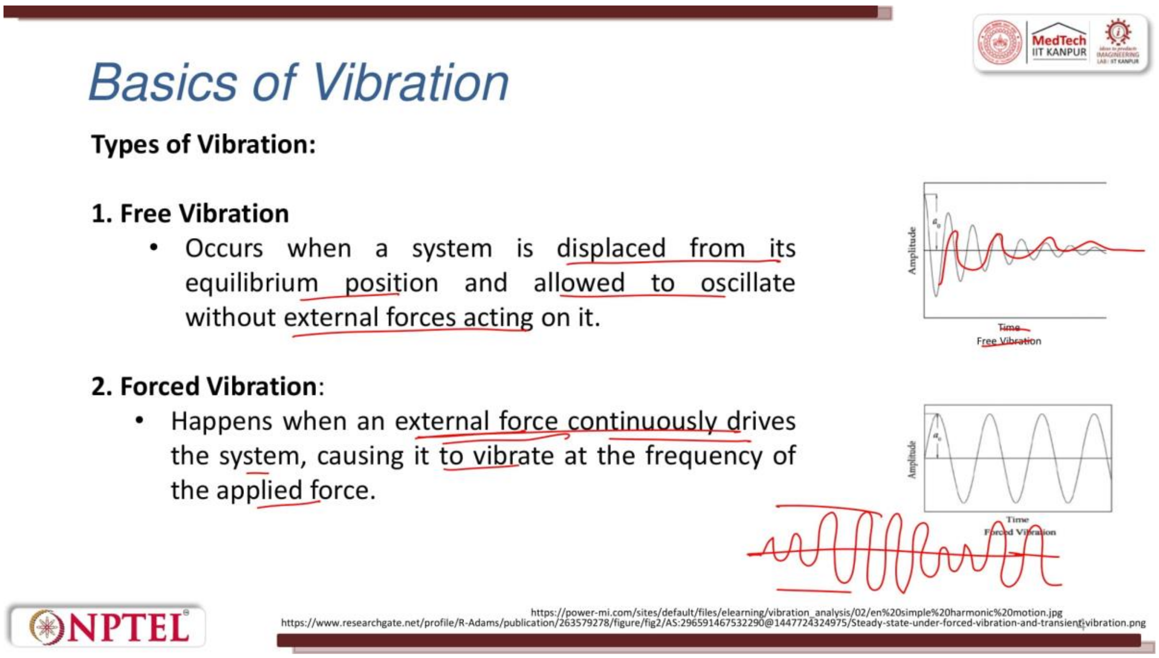
First question is, what is Vibration? Vibration is the repetitive oscillation of a mechanical system around an equilibrium point. There is an equilibrium point here, oscillation up and down.

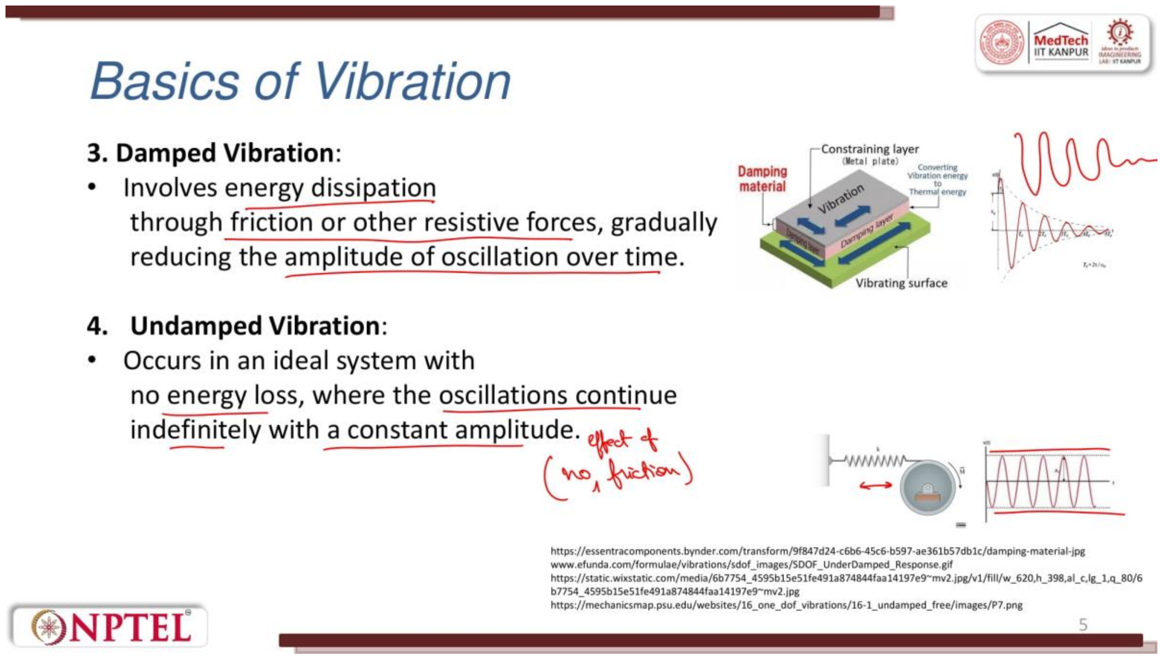
This is a sine wave that is showing the vibration. So, it is moving at a constant speed. It occurs when a system is displaced from its rest position. An experience is a restoring force that tries to return it to that position resulting in to and fro motion.



Types of vibration are Free vibration, Forced vibration, Damped vibration and Undamped vibration.

This is a time free vibration. Let us go through these. First is Free vibration. Free vibration occurs when a system is displaced from its equilibrium position and allowed to oscillate without external forces acting on it. Like you talk about a swing, kid is riding a swing and once the push is made, after that it is trying to come to its equilibrium position by itself.

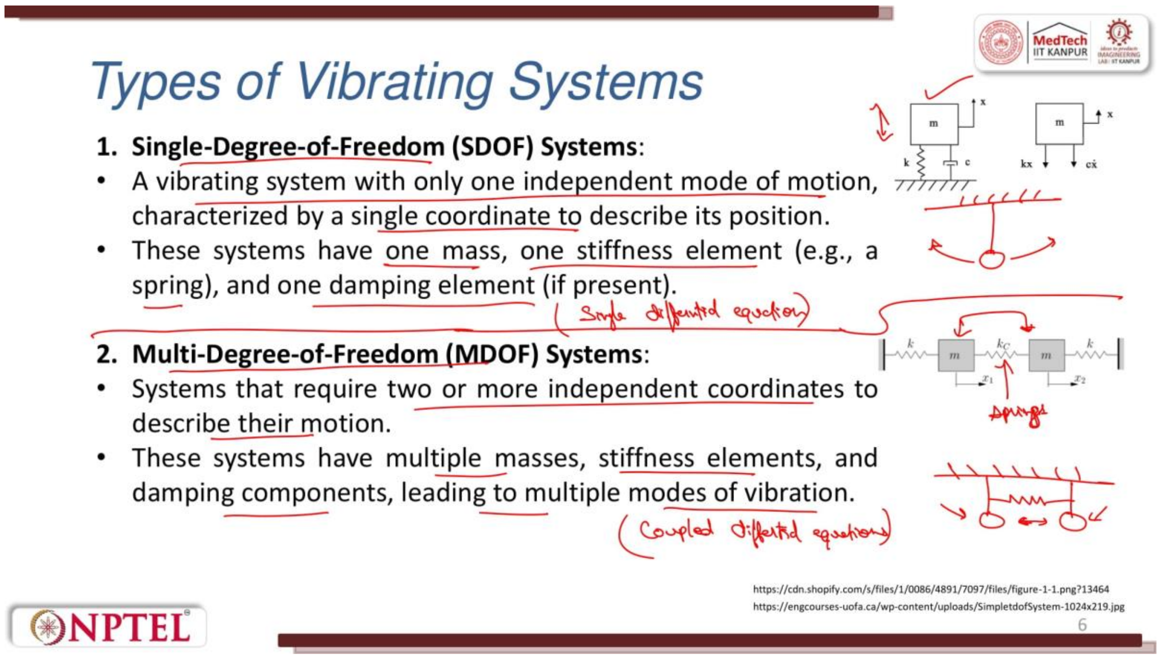
So, this is a free vibration, slowly you see it is coming to a equilibrium position, this is time free vibration. Forced vibration is when an external force continuously drives the system causing it to vibrate at a frequency of the applied force; for example that is when you are trying to ride a bike or you drive a car, you are experiencing some vibration because continuously engine is acting as an external force to continually drive the system. We can also take an example such as washing machine. Washing machine is running continuously it is vibrating because the motor is rotating through electrical energy. So, this is forced vibration that could be having varying amplitude as well depending upon the load when washing machine is running at a maximum speed of spinning rating it will be high it could come down it could again go higher down something like that. This is forced vibration it depends upon the external force the intensity given by external force determines its amplitude.



Then is Damped vibration. Damped vibration involves energy dissipation. Slowly energy is getting dissipated through friction or other resistive forces gradually reducing the amplitude of oscillation over time. So, this is the damping material.

The vibration is happening on the crystalline layer. Damping material is helping to restrict the force so that the friction is reduced. So in this figure, the vibration is being damped from the maximum to almost the equivalent. Example of the damped vibration could be the car suspension absorbing shocks. Once your car travels through a dump hole, suddenly you experience a shock.

The shock slowly on a plain road, you will experience it is being damped and car then runs smoothly. So, that is damped vibration. Undamped vibration occurs in an ideal system with no energy loss where the oscillations continue indefinitely with a constant amplitude. So, an ideal spring mass system where spring mass system is working, this is a kind of a undamped vibration where it is continuously a constant amplitude vibration. So, there is no friction or I could say no effect of friction.

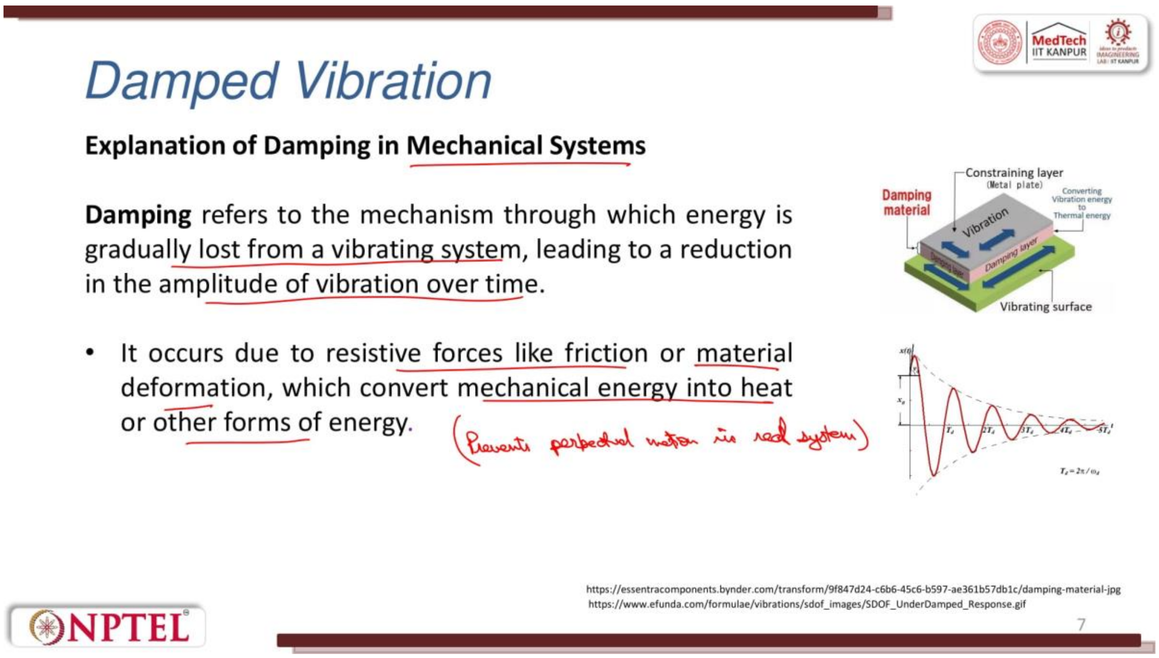


Let us now talk about the Vibrating systems. Vibration systems could be Single-Degree-of-Freedom or Multi-Degree-of-Freedom systems. A Single-Degree-of-Freedom system is a vibrating system with only one independent mode of motion characterized by a single coordinate to describe its position. So, this is a spring that is a Single-Degree-of-Freedom system. These systems have one mass, one stiffness element for example, a spring and one damping element if damping element is present.

Multi-Degree-of-Freedom system is a system that requires two or more independent coordinates to describe their motion. These systems have multiple masses, stiffness elements and damping components leading to multiple modes of vibration. So, this is a multi-system where one mass is affecting the movement of other mass as well. So, this becomes a multi-degrees of freedom system. So, here if we try to calculate that or put it in a mathematical form, single degree of freedom system is given by a single differential equation and here we need to have coupled or multi differential equations.

This is how we put it in a mathematical form. So, take examples for a single degree of freedom system could be a spring mass attached to a spring that oscillates up and down for a single degree of freedom. For a multi degree of freedom could be two or more masses. These are two masses which are connected by springs. But these masses move independently, but the degree of freedom is more than one.

If I give an example of a pendulum, a simple pendulum with one body swinging that is a single degree of freedom. In multi-degree of freedom, it has two pendulum suppose which are connected to each other using a spring. So, this becomes a pendulum. Multi-degree of freedom where motion of one pendulum is affecting the motion of the other pendulum. What is Damp vibration?



Explanation of Damping in Mechanical Systems. Damping refers to the mechanism through which energy is gradually lost from a vibrating system leading to a reduction in amplitude of vibration over time. It occurs due to resistive forces like friction or material deformation which convert mechanical energy into heat or other forms of energy. This is a law of motion. The perpetual motion is not possible.

So, this damping prevents perpetual motion. in real system in theory or in nodes this could exist, but in real systems perpetual motion is not possible.

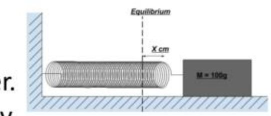
Damped Vibration

Damping Types:

1. **Viscous Damping**:
- Caused by a fluid's resistance (e.g., oil or air) to the motion of the vibrating system.
- The damping force is proportional to the velocity of the moving object. — shock absorbers in automotive systems

2. **Coulomb (Dry Friction) Damping**:
- Occurs when two surfaces in contact slide against each other.
- The damping force remains constant, regardless of velocity, and acts in the opposite direction to motion.

— sliding motion systems, such as brakes



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Types of damping if we try to talk about it could be Viscous damping or Dry Friction damping or Coolant damping. It could also be Structural or Hysteresis damping. Viscous damping is caused by fluids resistance.

For example, oil or dirt to the motion of vibrating system. The damping force is proportional to the velocity of the moving object. The common viscous damping example could be the shock absorbers. There is always you get oil filled shock absorbers in your motorbikes, in your cars. That oil is there that is a fluid that helps to absorb the shock and try to dampen the motion.

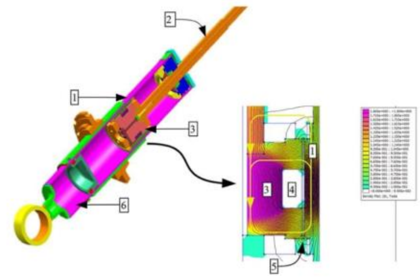
So, I would put an example as shock absorbers in automotive systems. Then comes dry friction or damping when it occurs between two services in contact that slide against each other. Damping forces remain constant regardless of velocity it acts in opposite direction to the motion. So, that occurs when sliding motion is there, sliding motion if I try to talk about again your automotive system brakes, the brake shoes when it get in contact with the brake drum, the sliding motion is getting stopped. So, that is a dry friction without having any fluid. I will put it as sliding motion systems such as breaks.

Damped Vibration

3. Structural (Hysteresis) Damping:

- Arises from internal friction within a material as it deforms and returns to its original shape.
- This type of damping is dependent on the strain experienced by the material.

metal structures, beams,
machine frame
vibration getting absorbed by the material deformation



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Then comes Structural or Hysteresis damping. This arises from internal friction within a material as it deforms and returns to its original shape. This type of damping is dependent on the strain experienced by the material. So, these kinds of damping is majorly found in metal structures or in beams

or machine forms or machine frames where vibration is absorbed by the material deformation only. When material is getting deformed, the frame is getting deformed, the vibration is absorbed here. This damping is because of the vibration getting absorbed by the material deformation. It depends upon the strain that is being experienced by the material.

Natural Frequency and Resonance

Natural Frequency

- The natural frequency is the rate at which a system oscillates when disturbed from its equilibrium position without external forces acting on it.
- It depends on the system's mass and stiffness, and each system has one or more natural frequencies based on its structure.
- Calculated using the formula

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

- where f_n is the natural frequency, k is the stiffness, and m is the mass of the system.

- **Significance**: The natural frequency is crucial for understanding how a system responds to vibrations.

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Let us now talk about Natural Frequency and Resonance. Natural frequency is the rate at which a system oscillates when distributed from its equilibrium position without external forces acting on it. Natural frequency, if I put certain examples like you put a child on a swing and you try to push the child, the swing goes higher and it goes faster. This is because you are matching the swing's natural frequency. For example, the guitar, how does it operate? Different string in the guitars gives you different pitch.

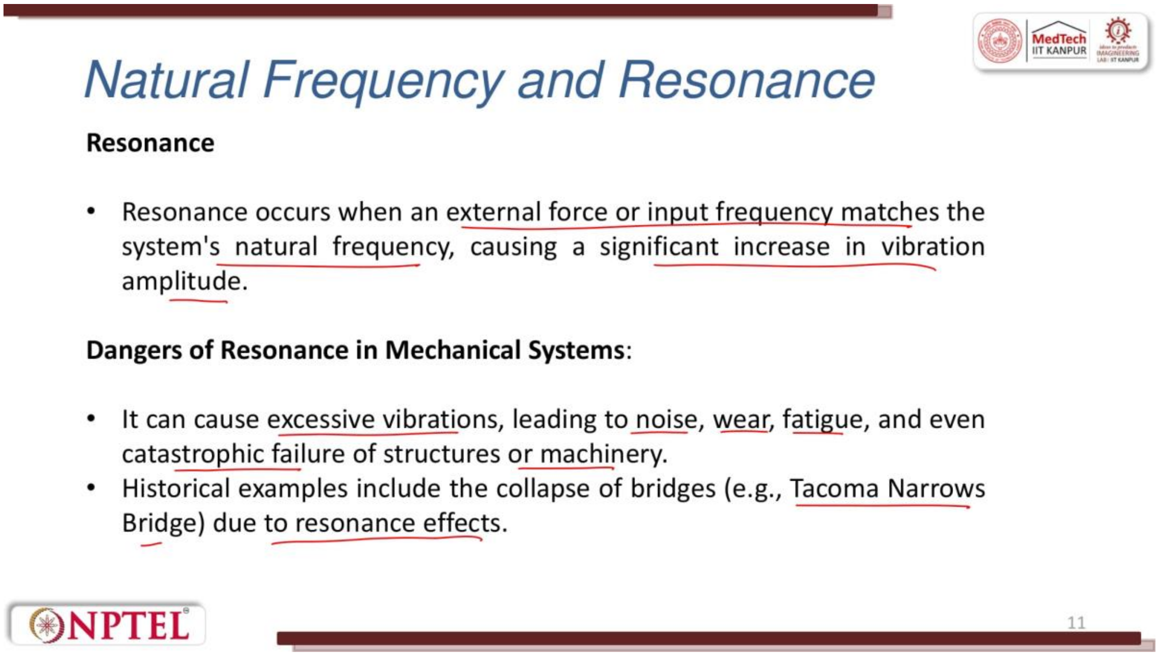
The pitch could be high, pitch could be low depending upon the thickness of the string of the guitar. When a guitarist pull up that string, you hear a sound that is having different pitch or lower pitch if it is thick. If it is having smaller or thickness is lower, you hear a high pitch because natural frequency of the material of that string is something that is giving you that pitch. So, natural frequency depends upon the system's mass and stiffness. More stiff the string of the guitar is, higher would be the pitch.

Less stiff, lower pitch would be there. So, that is stiffness is one factor, system mass is another factor. And each system has one or more natural frequencies based upon its structure. It is calculated using formula

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

where k is stiffness and m is mass of the system. Significance: natural frequency is crucial for understanding how a system respond to vibration.

It is important to understand how operating a machine close to natural frequency can lead to resonance making this concept more important in design.



So, for that let us try to come to the concept of Resonance. Resonance occurs when an external force or input frequency matches the system's natural frequency causing a significant increase in vibration amplitude. Taking the example of guitarist, guitarist could break a glass. It could break a glass because the glass has a natural frequency.

When you try to match that natural frequency of the sound that guitar is reproducing, the system or the glass could shatter down. That is the breaking of the glass could happen. That is when a sound wave strikes an object, it is already vibrating at its particular natural frequency. Even if that frequency happens to match the resonant frequency of the object hitting, then resonance occurs. So, there are certain dangers associated with resonance.

It can cause excessive vibrations leading to noise, wear, fatigue and even catastrophic failure of structures or machinery. Historical examples include collapse of bridges. For example, Tacoma narrows bridge due to resonance effects only.

Introduction to Acoustics

Basic Principles of Sound Waves and Acoustics

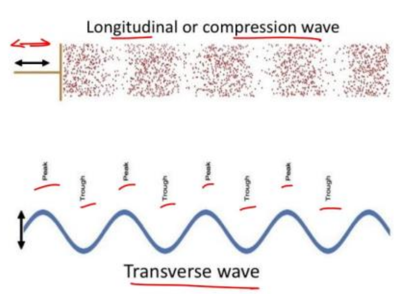
- Acoustics is the branch of physics that deals with the study of sound waves—how they are generated, propagated, and perceived.
- Sound is a mechanical wave that travels through a medium (solid, liquid, or gas) due to the vibration of particles in the medium.

Now, let us talk about acoustics. Basic Principles of Sound Waves and Acoustics. Acoustics is the branch of physics that deals with study of sound waves and how they are generated, propagated and perceived. Sound is a mechanical wave that travels through a medium that could be solid, liquid or gas due to the vibration of particles in the medium.

Introduction to Acoustics

Sound Waves: Longitudinal and Transverse Waves

1. **Longitudinal Waves**: In these waves, the particles of the medium vibrate parallel to the direction of wave propagation. Sound waves in air are longitudinal waves, where areas of compression and rarefaction move in the direction of the wave.
2. **Transverse Waves**: In transverse waves, the particles vibrate perpendicular to the direction of wave propagation. While sound in gases and liquids primarily travels as longitudinal waves, it can propagate as transverse waves in solids.



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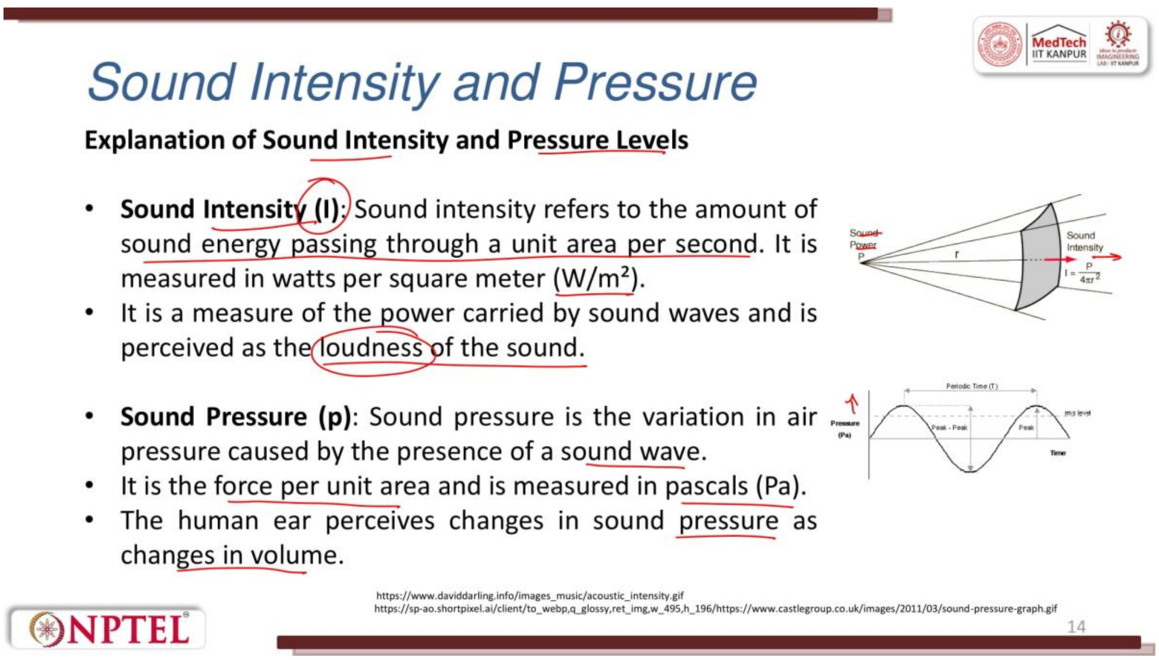
Sound waves could be Longitudinal and Transverse. In these waves, the particles of the medium vibrate parallel to the direction of the wave propagation. Sound waves in air are longitudinal waves where areas of compression and rear friction move in the direction of the wave.

Transverse waves. In Transverse waves, the particles vibrate perpendicular to the direction of the wave propagation. So, this is a transfer wave where peak and trough is being produced here. In a specific pitch, in longitudinal wave, it is moving in the direction of the wave propagation only. It is longitudinal or compressive wave.

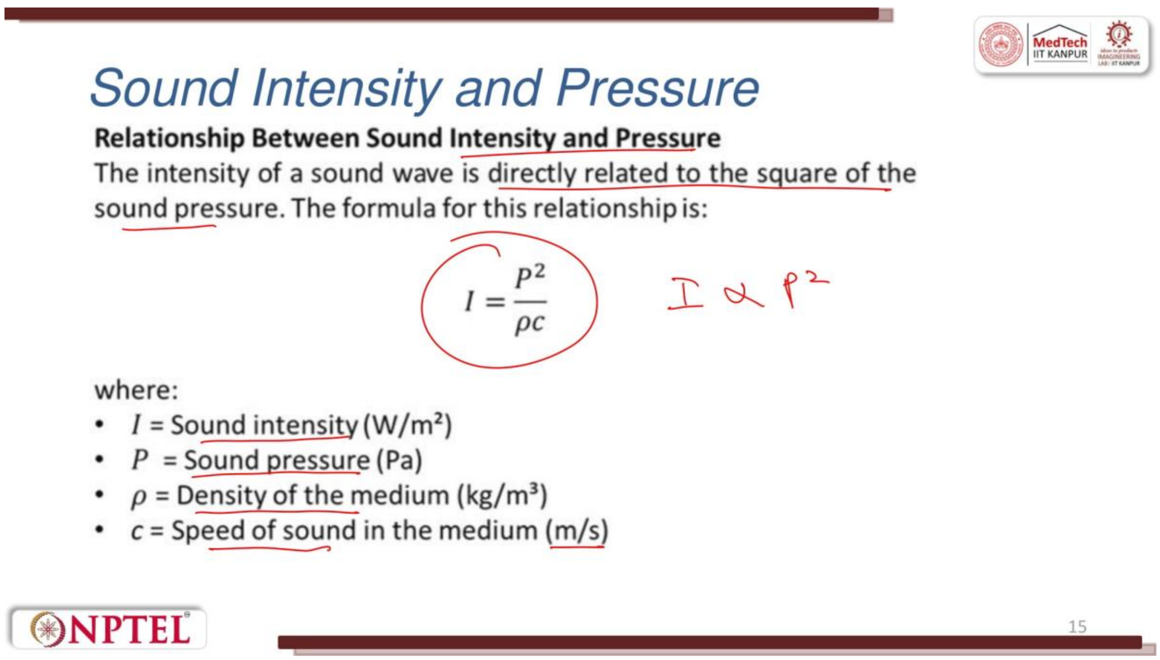
While sound in gases and liquids primarily travels as longitudinal waves, it can propagate as transfer waves in solids.



Explanation of Sound Intensity and Pressure Levels. Sound intensity I. Sound intensity refers to the amount of energy passing through a unit area per second. That is, it is given in watts per square meter (W/m^2).

It is a measure of power carried by sound waves and is perceived as the loudness of the sound. So, intensity means loudness. Sound pressure is the variation in air pressure caused by the presence of a sound wave. This force per unit area is measured in pascals. Human air perceives changes in sound pressure as changes in volume.

So, this is what it is showing sound power, that is sound intensity, how it is saying. So, this is sound pressure that is being shown in pascal.

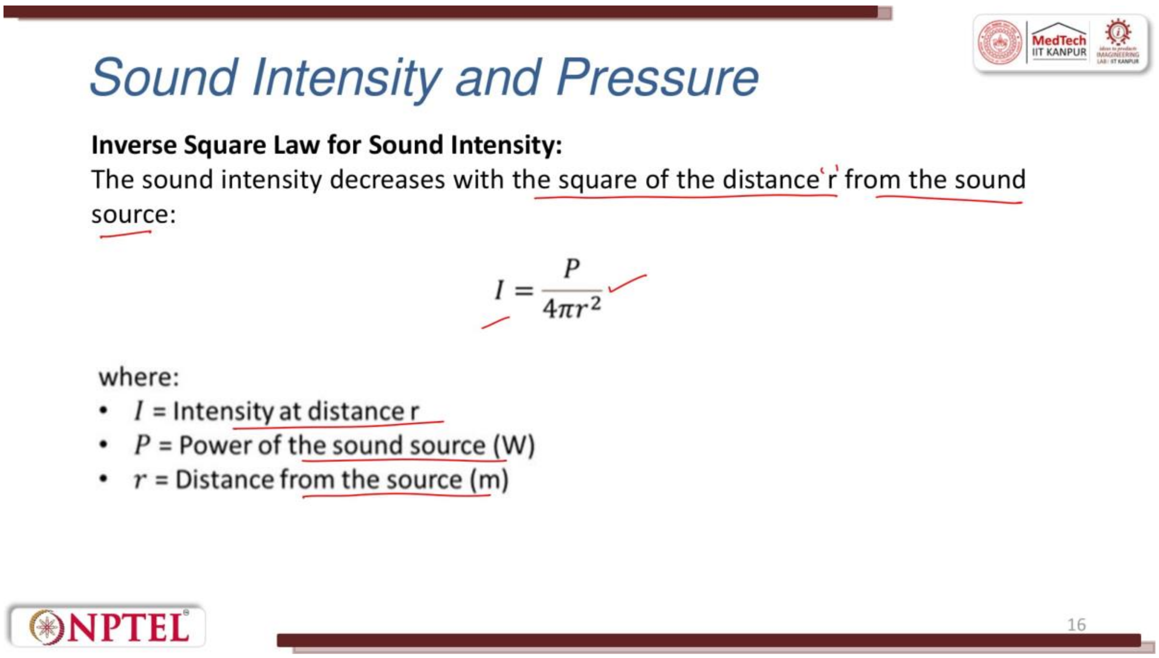


If I try to put a mathematical relationship for them between Sound Intensity and Pressure that could be put in this way. The intensity of a sound wave is directly related to the square of the sound pressure. The formula of this relationship is

$$I = \frac{P^2}{\rho c}$$

where:

- I = Sound intensity (W/m^2)
- P = Sound pressure (Pa)
- ρ = Density of the medium (kg/m^3)
- c = Speed of sound in the medium (m/s)

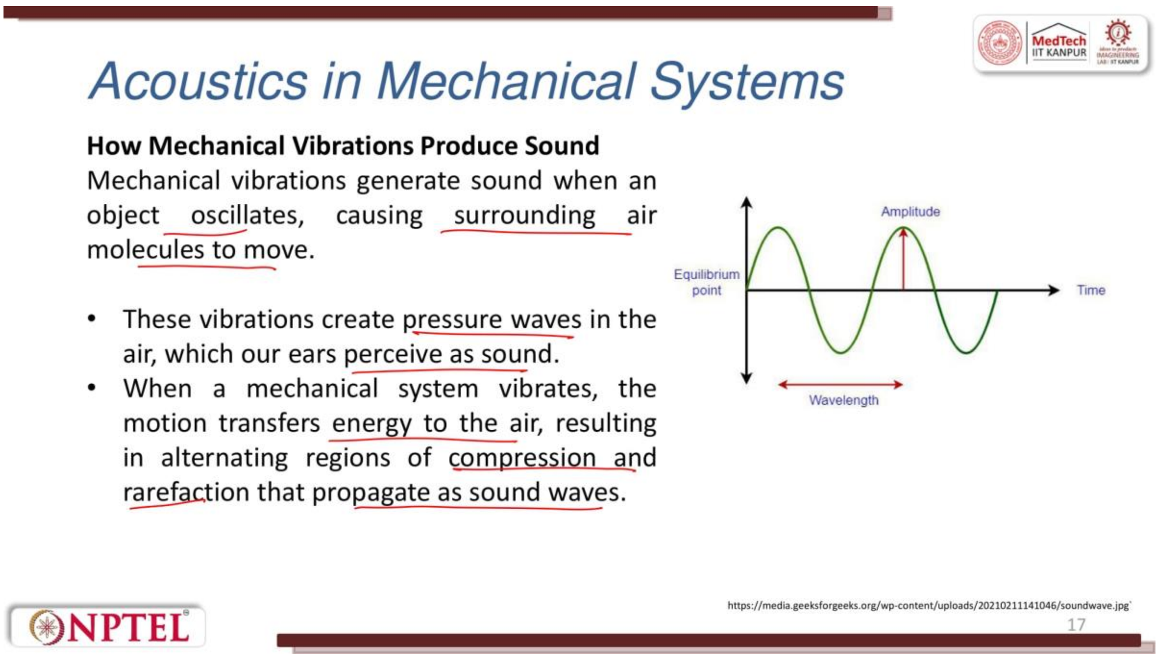


Also, there is inverse square law for sound intensity in which it is said that

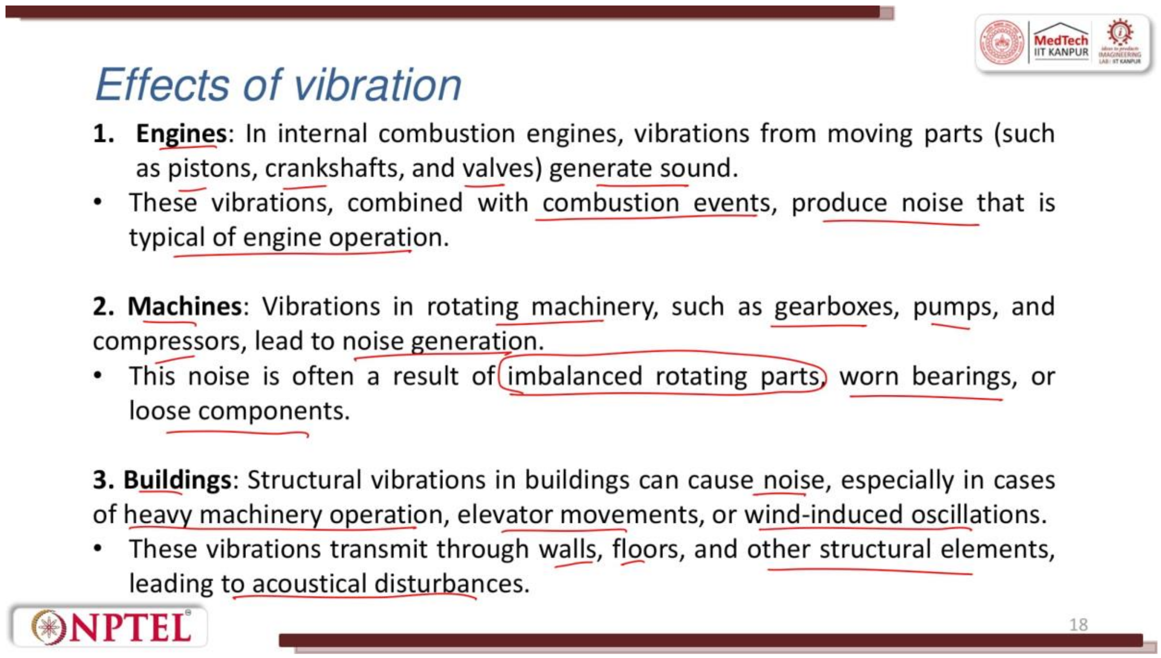
$$I = \frac{P}{4\pi r^2}$$

where:

- I = Intensity at distance r
- P = Power of the sound source (W)
- r = Distance from the source (m)



Now how Mechanical vibrations produce Sound? Mechanical vibrations generate sound when an object oscillates causing surrounding air molecules to move. So, there is an equilibrium point from which the amplitude and pitch or wavelength could vary. These vibrations create pressure waves in the air which are ears perceive as sound. When a mechanical system vibrates, the motion transfers energy to the air resulting in alternating regions of compression and rarefaction that propagate as sound waves.

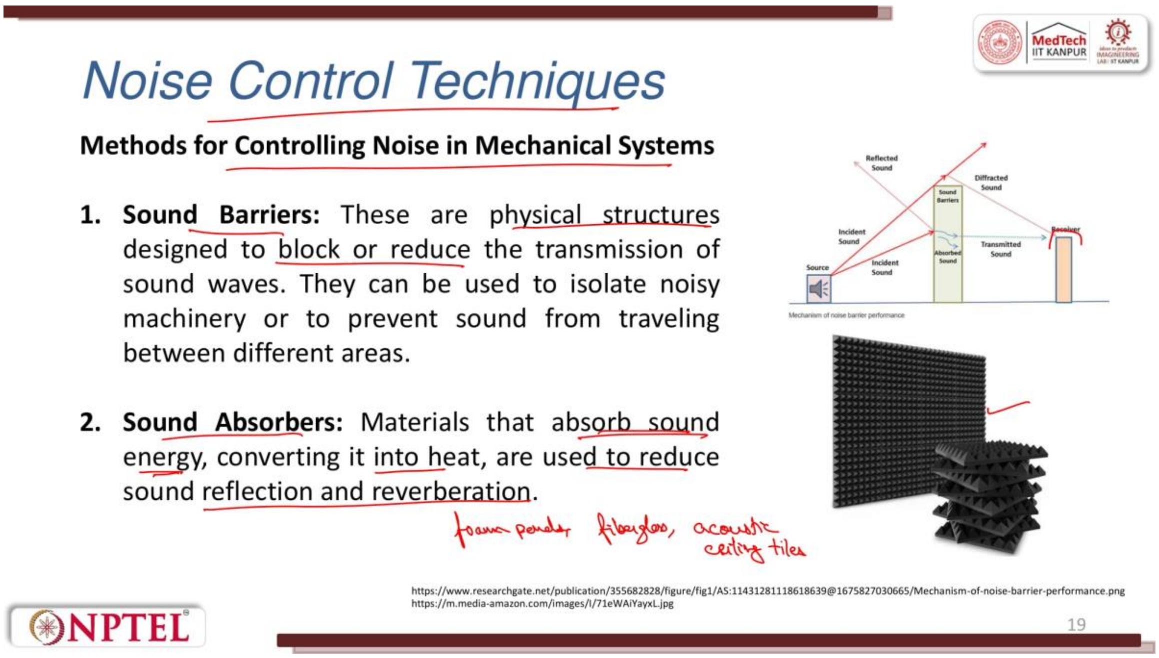


Effects of vibration could be put in this way in engines, in machines, in buildings. In internal combustion engines, vibrations from moving parts such as pistons, crankshafts and valves generate sound. These vibrations combined with combustion events produce noise that is typical of engine operation in machines vibrations, in rotating machinery such as gearboxes, pumps, compressor lead to noise generation.

This noise is often a result of imbalanced rotating parts or worn bearings or loose components. It is there in machines in building as well in construction or in structural systems.

Structural vibrations in buildings can cause noise especially in cases of heavy machinery operation, elevator movements or wind induced oscillations. These vibrations transmit through walls, floors or other structural elements leading to acoustic disturbances. Now, the point is how do we curb the vibrations? How do we control the vibrations? Because something that is happening in my neighborhood that should not affect me.

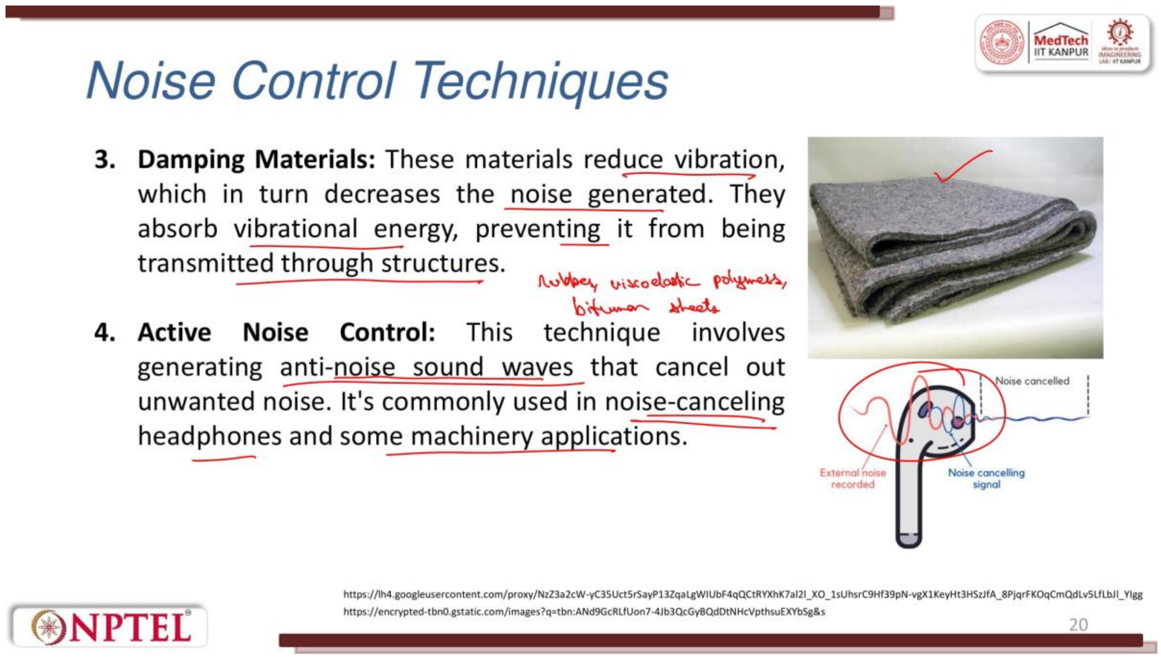
We close the door. This is a studio where recording is happening. We have acoustic material all around so that the vibration is not there. So, vibration damping systems are there.



Noise Control Techniques. Methods for Controlling Noise in Mechanical Systems. Sound barriers, Sound Absorbers, damping materials, active noise control, this could all be used. Sound barriers. These are physical structures designed to block or reduce the transmission of sound waves. They can be used to isolate noisy machinery or to prevent sound from travelling between different areas.

So, sound barriers could be put. For example, this is an incident sound that is coming, source is there. This sound barrier does not allow the sound to be reached through receiver with the same intensity. So, transmitter sound, here the barrier absorbs the sound to the maximum level and receiver does not receive or does not receive the sound that loud whatever is coming from the source. Sound absorbers, materials that absorb sound, energy.

Converting it into heat are used to reduce sound reflection and reverberation. So, sound absorbing materials could be certain porous plastic medium sponges or so. So, this could be I would put it here foam panels, fiberglass or maybe acoustic ceiling files.



Next is Damping Materials, these materials reduce vibration which in turn decreases the noise generated, they absorb vibration energy preventing it from being transmitted through structures. So, this is a damping material you can see this cloth that is thick and it is porous could act as a damping material.

So, common damping material could be rubber, viscoelastic polymers and maybe some sheets such as bitumen sheets could be used. These are damping materials. Active Noise Control. This technique involves generating anti-noise sound waves that cancel out unwanted noise. It is commonly used in noise cancelling headphones and some machinery of applications.

So this is noise cancellation. So, if you purchase Apple iPod nowadays, those have noise cancellation feature in it. That means, whatever sound you wish to have, that is fine. If from outside or the external environment, some noise is coming, it will try to cancel that noise within the system here. So, this is noise being cancelled. That is, it generates anti-noise sound waves to cancel the noise.

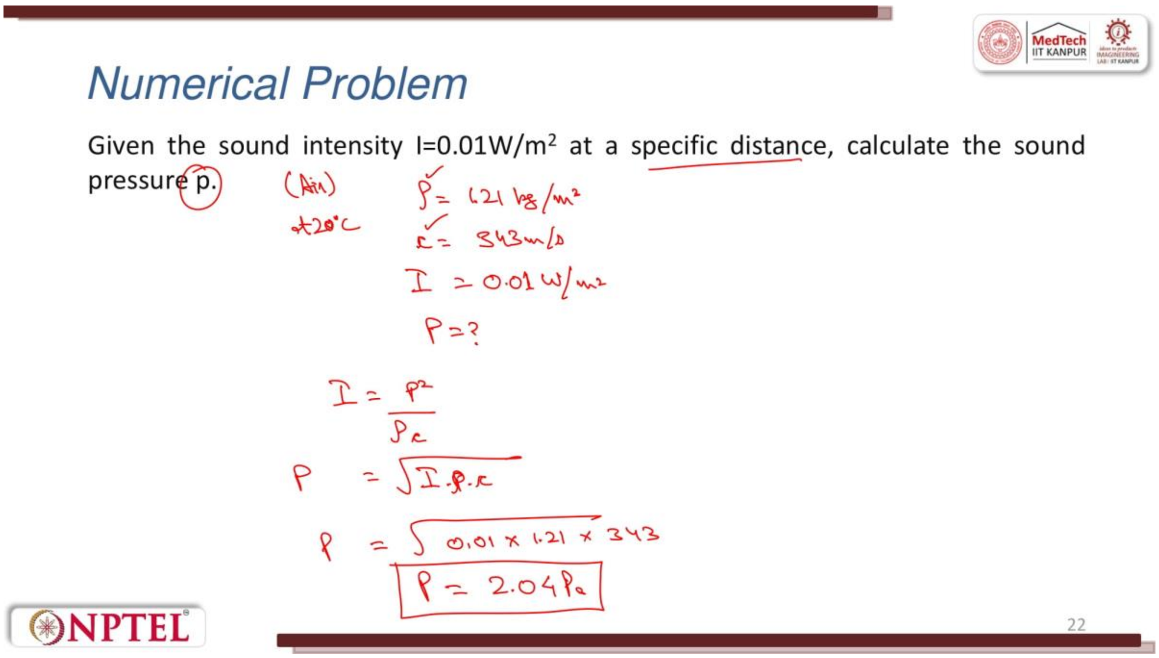
Noise Control Techniques

Practical Examples

- **Industrial Enclosures:** Encasing loud machinery in soundproof barriers to minimize noise in factories.
- **Automotive Industry:** Using damping sheets in car bodies to reduce road and engine noise.
- **Building Construction:** Installing sound-absorbing panels in walls and ceilings to control noise in commercial and residential spaces.

So, certain practical noise control techniques could be having industrial enclosures which is an encasing of loud machinery in soundproof barriers to minimize noise in factories. You might have observed in a manufacturing facility if water jet machine is there because water produces loud noise because of the stream of the pressure of the water. So, this machinery is put in a soundproof barrier to minimize the noise in factories.

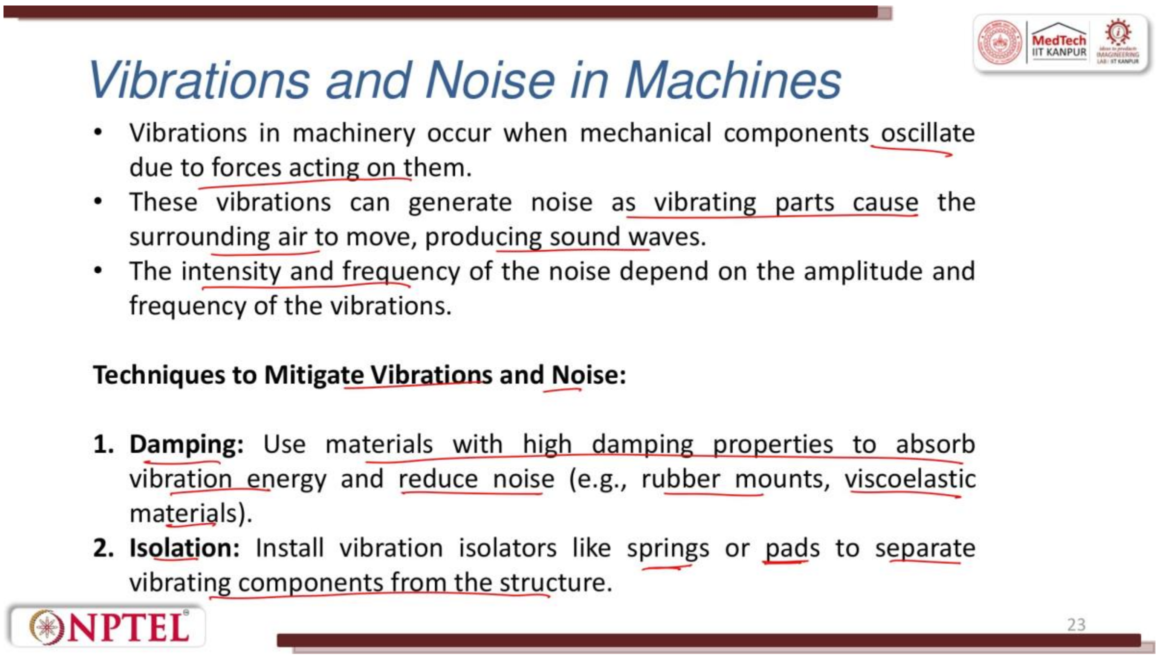
In automotive industry, using damping sheets in car bodies to reduce the road and engine noise that is used. In building construction, installing sound absorbing panels in walls and ceilings to control noise in commercial and residential spaces is there.



So, there is a small numerical statement that is there given a sound intensity with I is equal to 0.01 watts per meter square at a specific distance, calculate the sound pressure p. What we are given is only I and we have been given that it is in air and let us assume that this is happening in air and for air the density of air is typically 1.21 kilograms per.

I am taking of the density of air at 20 degree centigrade and speed of sound in air is 343 meters per second. I have been given intensity that is 0.01 watts per meter square. I need to find sound pressure P. As we know I is equal to p square by rho therefore, p is equal to under root of I into rho into c. Substituting the values this is equal to 0.01 into rho is 1.21 into 343 I got P is equal to 2.04 Pascal.

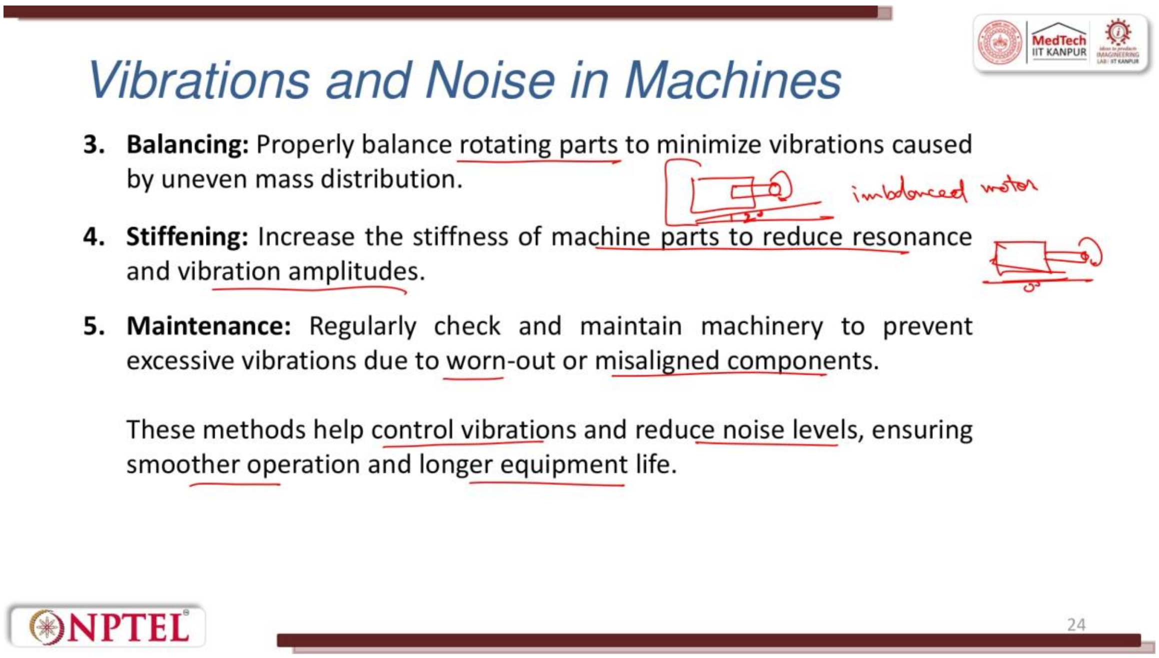
This was a very short numerical just to give a brief understanding of how do we calculate the sound pressure for a specific medium. For air at 20 degree the value of rho and C was taken.



Next is Vibration and Noise in Machines. Vibrations in machinery occur when mechanical components oscillate due to forces acting on them. These vibrations can generate noise as vibrating parts cause surrounding air to move producing sound waves.

The intensity and frequency of the noise depend on the amplitude and frequency of vibrations. Techniques to Mitigate Vibrations and Noise it could be damping, isolation, balancing, stiffening, maintenance, because we're talking about machine elements, use of material with high damping properties to absorb vibration energy and reduce noise is an important factor. For example, rubber mounts, viscoelastic materials, these all act as a damping material.

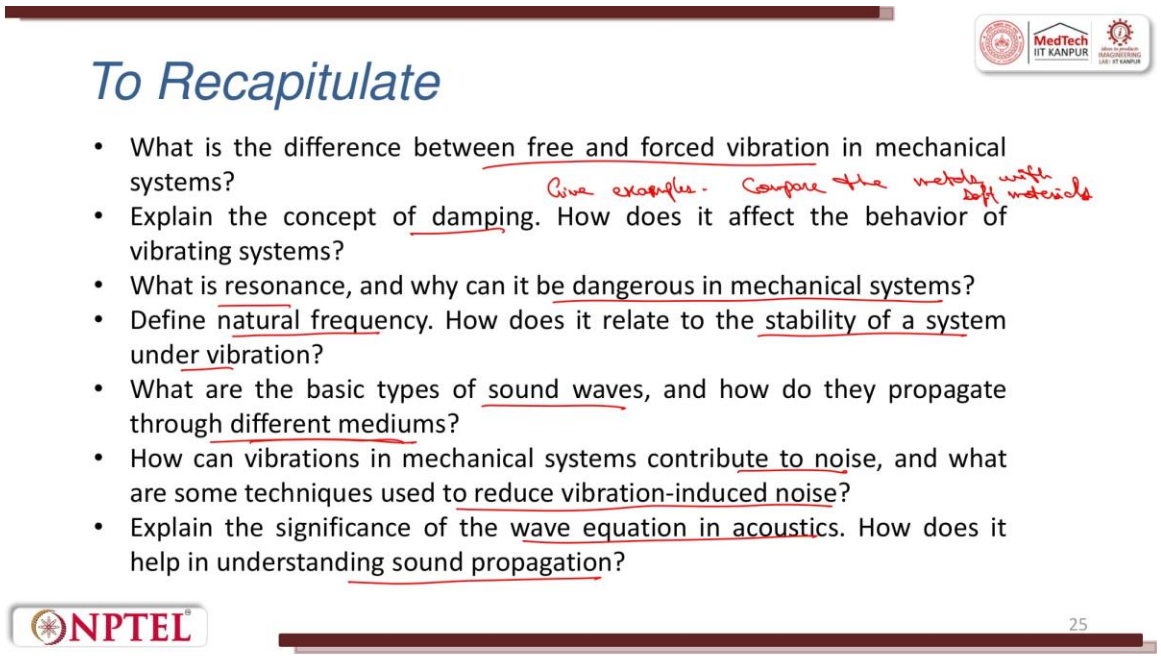
Install vibration isolators like springs, pads to separate vibrating components from the structure. If there is a vibrating component that could be put at a separate setup in the machinery, but that could be padded that could be put within a springs so that the vibration does not transfer to the main machinery.



Next is balancing that is properly balanced rotating parts to minimize vibrations caused by uneven mass distribution. For example, if there is a motor, if that motor is rotating and this is an angle at which motor is rotating that is 2 degree. So, this becomes an imbalanced.

This will produce vibration than a motor that is at exact 0 degrees. Stiffening. Increased stiffness of machine parts to reduce resonance and vibration amplitude that is a regular preventive maintenance schedule has to be there. If the temporary joints, that is nuts and bolts, the screws are getting loosened, those are to be tightened. So, stiffening of machine parts is also important.

Maintenance, a regular check and maintain machinery to prevent excessive vibrations due to worn out or misaligned components is important. These methods help control vibrations and reduce noise levels, assuring smoother operation and longer equipment life.



With this, I am closing my lecture on vibrations just to recapitulate. The questions that could be asked are what is the difference between free and forced vibration in mechanical systems? Explain the concept of damping.

How does it affect the behavior of vibrating system while explaining the concept of damping? Give some examples. And compare the metals with soft materials? How does the damping happens through them? What is resonance and why can it be dangerous in mechanical systems?

I have quoted some examples. You can take some more examples and try to answer this question. Define natural frequency. How does it relate to the stability of a system under vibration? What are basic types of sound waves and how do they propagate through different mediums?

How can vibrations in mechanical systems contribute to noise? And what are some techniques used to reduce vibration induced noise? Explain significance of wave equation in acoustics. How does it help in understanding sound propagation?

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So, there are references are being taken from the internet, the sources of the figures which I have taken are given in the slides.

With this I am closing this lecture on vibration. I will take one lecture on statistics in engineering or role of statistics in engineering, then I will close this course.

Thank you.