NOISE CONTROL IN MECHANICAL SYSTEMS

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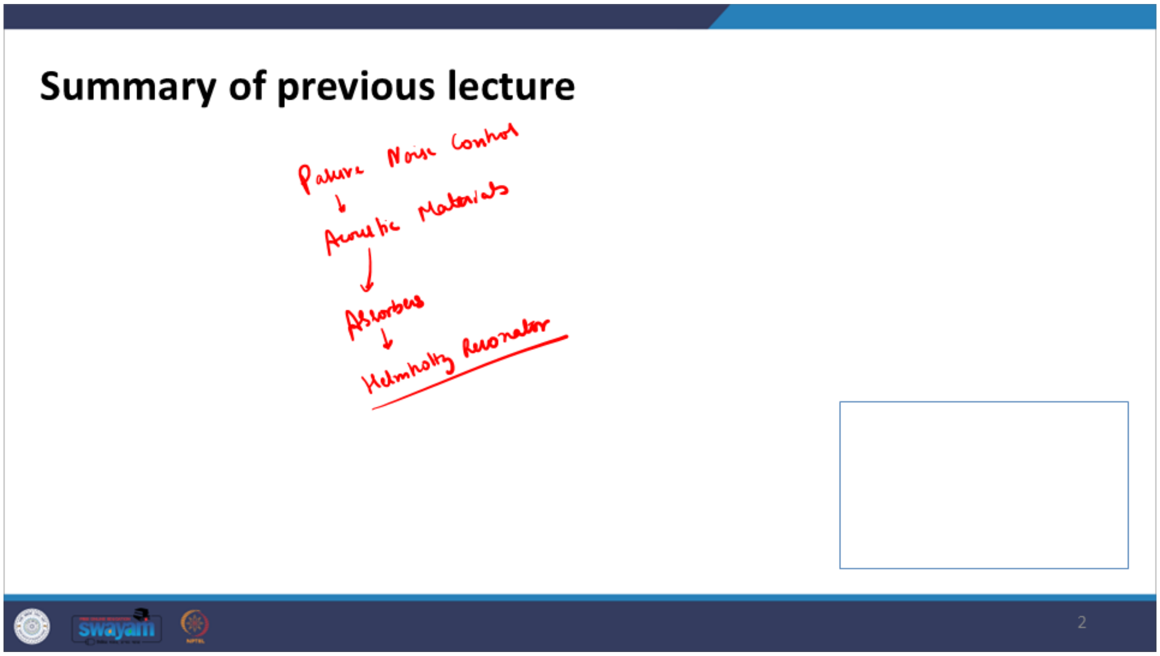
Week: 8

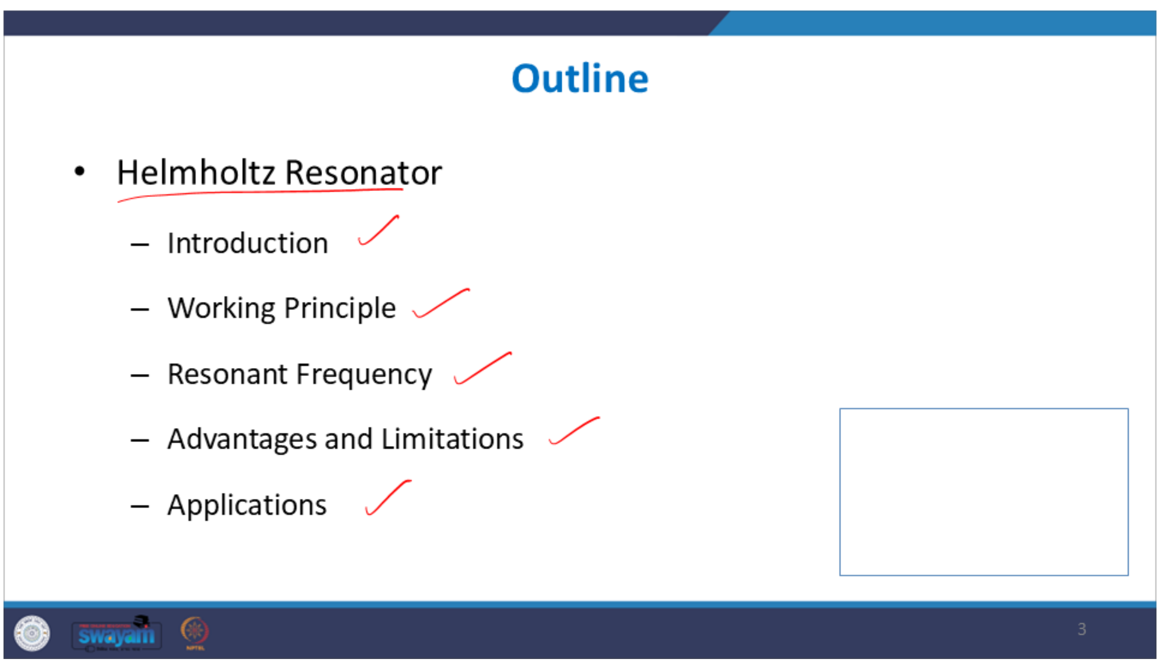
Lecture: 40

Lecture 40: Helmholtz resonators

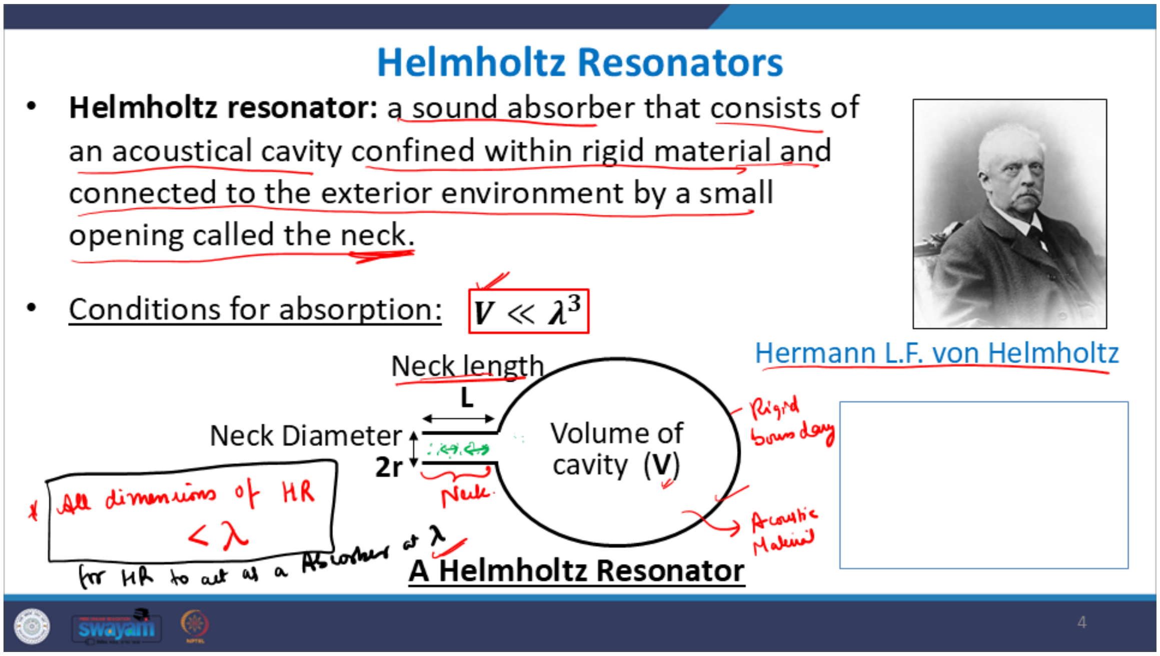
Hello and welcome to the series on noise control in mechanical systems with me, Professor Sneha Singh from the Indian Institute of Technology, Roorkee. And in today's lecture, we will discuss one type of resonating sound absorber, which is called the Helmholtz resonator. So, to quickly summarize, we are looking into the module of passive noise control, and within that, we are looking into the various kinds of acoustic materials which can be used for sound control, and one type of material is the absorbers. And within that, we have one type of absorber known as the Helmholtz resonator, which we will be discussing in today's lecture.



So, the introduction to the Helmholtz resonator, the working principle, the resonant frequency, the advantages and limitations, and the various applications of this resonator will be discussed.



So, what is a Helmholtz resonator? This is a kind of, as the name suggests, resonator, which means that it is some kind of structural element which undergoes resonance at some predefined frequencies, and due to the phenomenon of resonance, it is able to absorb sound.



It was proposed by the scientist Hermann L. F. von Helmholtz, and it is named after him. So, this is a sound absorber. It consists of an acoustical cavity which is confined within some rigid material or some rigid boundaries. and then it is connected to the exterior environment by a small opening called the neck. Ok. So, it looks something like this.

You have some kind of acoustical cavity. It can be of any shape. It can be rectangular in nature, cuboidal in nature. It could be cylindrical in nature, spherical in nature. So, any kind of acoustical cavity of any shape.

And this capital V becomes the volume of the acoustical cavity, which is confined within a rigid boundary. So, the boundaries have to be rigid. This is the rigid boundary within which this acoustical cavity exists. It contains an acoustic medium. The most common medium used for a Helmholtz resonator is air.

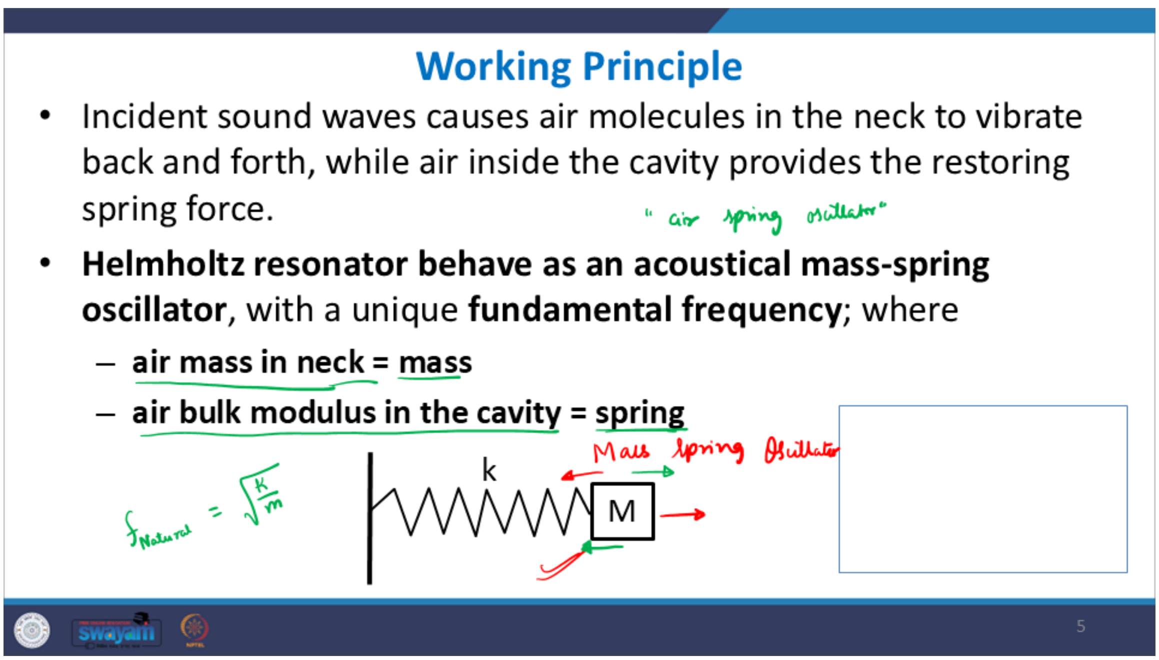
So, usually it contains the confined acoustic medium, most likely air. And this cavity is connected to the outside wall through some kind of extended opening, which is smaller in cross-sectional area and has a length or an extension called the length. Or the neck length.

So, this is called the neck of the Helmholtz resonator. The diameter becomes twice r, where r is the radius of the neck, and L becomes the length of this neck.

So, which connects the cavity to the outside environment. And V becomes the volume. So, this is your typical Helmholtz resonator. Now, this will act as an absorber. So, the first condition for that is that the volume of the acoustical cavity has to be much smaller compared to the cube of the wavelength, or in other words, I can say that all dimensions

of the Helmholtz resonator. So, be it the length of the neck, the diameter of the neck, or the dimensions of the cavity. So, all dimensions of this Helmholtz resonator have to be smaller than the wavelength under consideration. So, that it can act as an absorber at that wavelength. This becomes a generic condition for a Helmholtz resonator to act as an absorber at the lambda wavelength of the sound wave.

So, let us see what the working principle of this particular resonator is. So, what happens is that here you have



the incident sound waves hitting. So, from the outside environment, suppose there is some noise source which is creating these pressure fluctuations or sound waves. Which hit the neck, and when they hit the neck, they can create vibrations in the molecules of the neck.

Ok, So whatever air molecules are there. So, when they hit it they create vibrations or the back and forth motion of the air particles in the neck, but here the neck is being connected to a confined air cavity right. So, it has it is connected by rigid walls. So, the air by default it is a compressible, it is a compressible medium and it has a resistance to compression ok. And similarly it has its own resistance to expansion.

So, when the sound waves they are hitting the neck they are vibrating the air molecules in the neck which in turn is trying to as the molecules in the as the vibrations or the fluctuations of the air particles they reach through the neck into the cavity these vibrations they tend to sort of compress the air molecules within the cavity and expand it. So, the vibrations essentially They try to compress and expand the air molecules within the confined cavity but because the air molecule is confined it has no way to you know get around. If suppose the cavity there was no confined cavity or there was no rigid boundaries. then whatever these vibrations were they would pass through you know the as the particles are compressing and expanding they would have other spaces to fill and they wouldn't be that level of resistance but here the air molecules within the cavity they have nowhere to go so when the air particles from the neck which are vibrating back and forth are hitting and trying to

hit and compress the air particles in the cavity they have nowhere to go and when they try to expand again they have nowhere to go and therefore they create a little bit of resistance because they have nowhere to they have no spaces to fill. Suppose some expansion happens or contraction like that so in that case so these confined the molecules within the confined cavity they have their own resistance to compression and expansion and this becomes like their inherent stiffness. So, they act like an oscillator you can think of a mass spring system you know a typical mass spring oscillator. So, in the field of

Know vibrations, you come across various oscillators where we have a mass-spring system. What is it? You have a rigid boundary connecting one end of the spring, and on the other end of the spring, you have got some mass which is free to fluctuate. So, when you push the mass of the spring—if you look at this figure here—what you do is you are trying to, let's say, push the mass. Using this, suppose you are applying the force and trying to push the mass in this direction. What will happen? Due to the spring force, it has its own stiffness; it has resistance to expansion and contraction. So, the spring force will act in the opposite direction to restore it to its original motion. In the same way, suppose you had applied the force and tried to contract it in this way. Then, the spring force will again act in the opposite direction and try to restore the spring back to its original length. And this is how, if you suppose stretch a spring with a mass and just leave it, it sets into vibration or oscillatory motion.

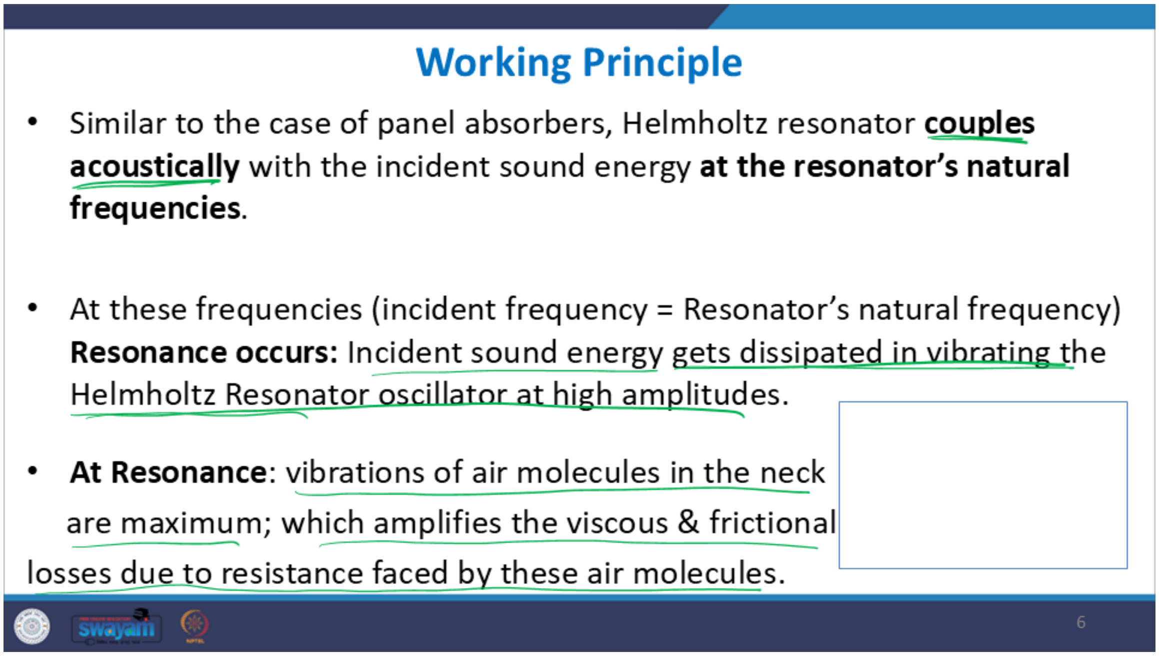
So, here also, this particular Helmholtz resonator acts like a mass-spring oscillator. Here, the air particles in the neck of the cavity. So, okay, all the air particles present here in the neck. And the mass of them—because they are the molecules which are vibrating back and forth—and their vibration back and forth is being resisted by the compressed cavity inside this confined space. So, the compressed air molecules in the confined cavity.

So, these are trying to vibrate back and forth, and this is acting as the resistance to their expansion and contraction. So, the mass becomes these masses of the air molecules in the neck, which are vibrating back and forth, and they are being resisted by the decompressibility or the bulk modulus of the air within the cavity, okay. So, their motion is being opposed by the bulk modulus of the air within the cavity of the resonator. So, that acts as your spring element, okay. So, this becomes the mass, and this bulk modulus of the air within the cavity is resisting the expansion and contraction, which is being initiated by this back-and-forth motion.

So, this becomes your spring, which is trying to resist the motion, and hence, oscillatory motion is set. So, this overall system behaves as a mass-spring oscillator, which means it behaves as a kind of oscillator, and it has its own unique fundamental frequency. So, for example, in this spring system, the natural frequency of this mass-spring oscillator is the square root of k divided by m. In the same way, we have a Helmholtz resonator where the spring constant is simply due to the bulk modulus in the cavity. So, depending on the volume of the cavity. Okay, and depending on the medium considered, you will have a certain bulk modulus, which will correspond to a certain k of the system, and the air mass would then depend on the volume of the neck.

So, the length of the neck, as well as the surface area of the neck, will determine the mass. So, it will have its own natural frequency. So, now that we know that the Helmholtz resonator acts as a mass-spring oscillator, and it is sometimes also called an air-spring oscillator because the air element is acting as a spring, okay. So, it is also called an air-spring oscillator because here the confined air is acting as a spring element. So, what happens in this kind of thing, you know,

So, suppose you have an incident sound wave that is at the same frequency as the fundamental frequency of this resonator; then, there will be something called acoustical coupling. So, we have already seen the noise control phenomenon in a panel resonator. So, whenever the incident frequency corresponds to the frequency with which the sound waves are hitting a panel absorber, if the incident frequency matches the natural

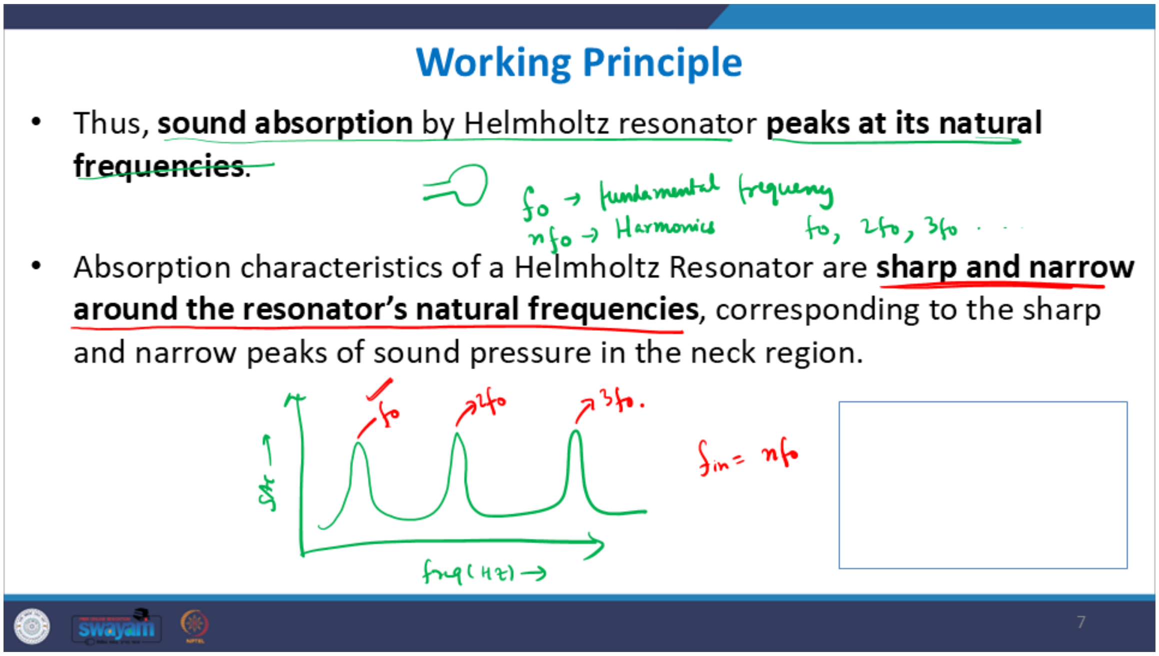


frequency of the vibration of these panels, then there is resonance, and whatever sound waves are hitting are being used up in driving the panel back and forth, and the energy gets dissipated. Here also, in the same way, whenever the incident frequency is the same as the fundamental frequency of this Helmholtz resonator, there will be acoustic coupling.

So, whatever the incident energy is, it will get dissipated in vibrating the Helmholtz resonator at a very high amplitude. So, resonance will be set, and all the acoustical energy or the sound energy that was incident is now sort of getting absorbed inside the absorber. All of this energy is going in and is being used up in doing work to vibrate this absorber or the molecules of the absorber. So, in a way, you can say that the energy is getting absorbed and going inside this resonator.

So, at resonance, the vibrations of the air molecules in the neck are maximum, and this amplifies the viscous and frictional losses due to resistance faced by these air molecules, and also, whatever energy there is gets dissipated in doing work to vibrate this oscillator at high amplitudes.

Okay. So, therefore, because the maximum dissipation happens when there is resonance—which means when the frequency of the sound wave matches the frequency of the oscillator—then you have the maximum vibrations and hence the maximum energy dissipation. So, the sound absorption of this Helmholtz resonator will peak at its natural frequency, okay. So, let us say we have a particular Helmholtz resonator like this, and let



us say f0 is its first or fundamental frequency or the first natural frequency, and then we have all the multiples of it, which become its higher harmonics, okay.

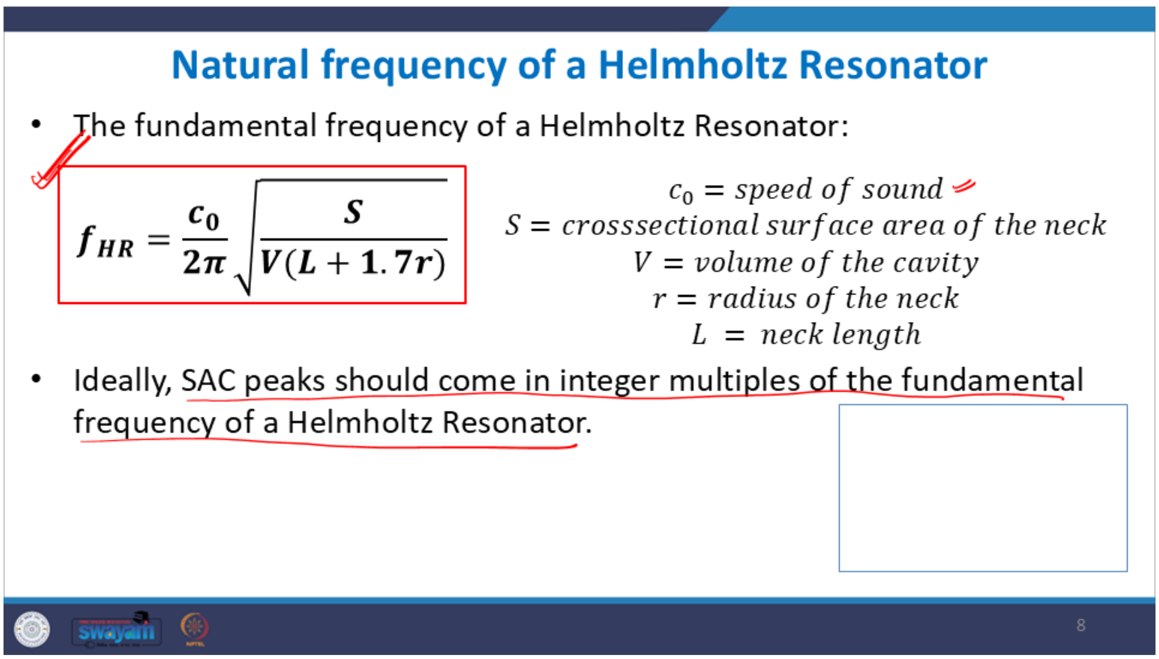
Because the resonator will have frequencies in integer multiples of f0. So, the first frequency would be f0, followed by 2f0, 3f0, and so on. So, here, the sound absorption of this resonator should look something like this and you have this, let us say, the SAC. So, wherever resonance happens, you have maximum energy dissipation going into the absorber.

So, it should look like this—sharp peaks repeating at some intervals, and these should correspond to the natural frequencies of the resonator and its harmonics. Ideally, this should be the case, but most of the time, due to other factors, the SAC may not exactly resemble this, okay? But because the phenomenon of resonance happens at specific frequencies—exactly when it is matching f0. So, only at that small, unique band where f, the incident frequency, is equal to some n times f0—only within those where the frequency matching occurs in that small, sharp band—would you get resonance, and beyond that, there is no resonance.

So, the characteristics would be very sharp and narrow. It would not be a broadband or a very broad-range kind of absorption. It would be a narrow absorption centered around the resonator's natural frequency. So, as you can see, compared to porous fibrous materials, both the panel absorber and the Helmholtz resonator can achieve low-frequency absorption because you can tune the dimensions of the system so that the first frequency comes at a lower hertz—some low frequency. So, you can attain a natural frequency at any desired range, at any desired point,

by tailoring the dimensions of the resonator, but the characteristics are going to be very sharp and narrow. So, you can only absorb at some specific target frequencies; you cannot do it for a wide range.

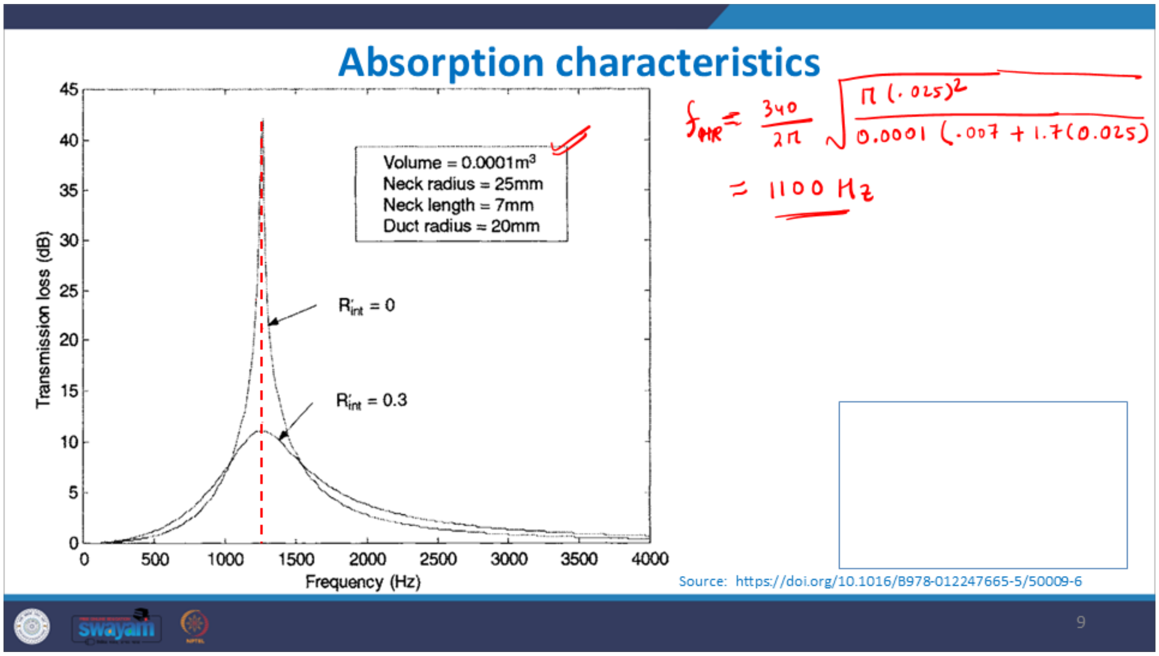
So, as you see, the absorption characteristic depends a lot on the fundamental frequency of the Helmholtz resonator. So, the fundamental frequency f0 this value here for this Helmholtz resonator is given by this expression: C0 divided by 2π times the square root of S divided by V times 1 plus 1.7 times R. So, this is one very important equation every noise control engineer or every student in this field must memorize by heart. Okay.



So, very important relation. C0 here is the speed of sound in whatever is the acoustic medium you are considering. In most of the cases it is air. So, it is the speed of the sound in the acoustic medium where the resonator is. Capital S is the cross sectional surface area of the neck and capital V is the volume of the cavity which is confined.

r is the radius of the neck and capital L is the neck length. So, ideally the SAC peaks should then be obtained at the integer multiples of this fundamental frequency of the Helmholtz resonator. So, it should occur at the first fundamental frequency which is given by this expression and then at its successive you know kind of multiples ok.

So, let us say for example, this is a particular you know absorption characteristics of a Helmholtz resonator with these dimensions. So, if you think about is let us find out its what is the fundamental frequency of this Helmholtz resonator we can simply write f of h r the fundamental frequency of the Helmholtz resonator.



It is C0 let us take it as 340 at room temperature by 2 pi and you have this S here S by V into L plus 1.7 r. So, S is the cross sectional surface area of the neck. So the neck radius is given assuming a cylindrical neck. If nothing is given you assume it is a cylindrical neck. So pi times of this pi r square should give you the cross sectional area of the neck. The volume of the cavity in the SI unit is given as this and then within that you have L plus 1.7r. So, the length is 7 millimeters.

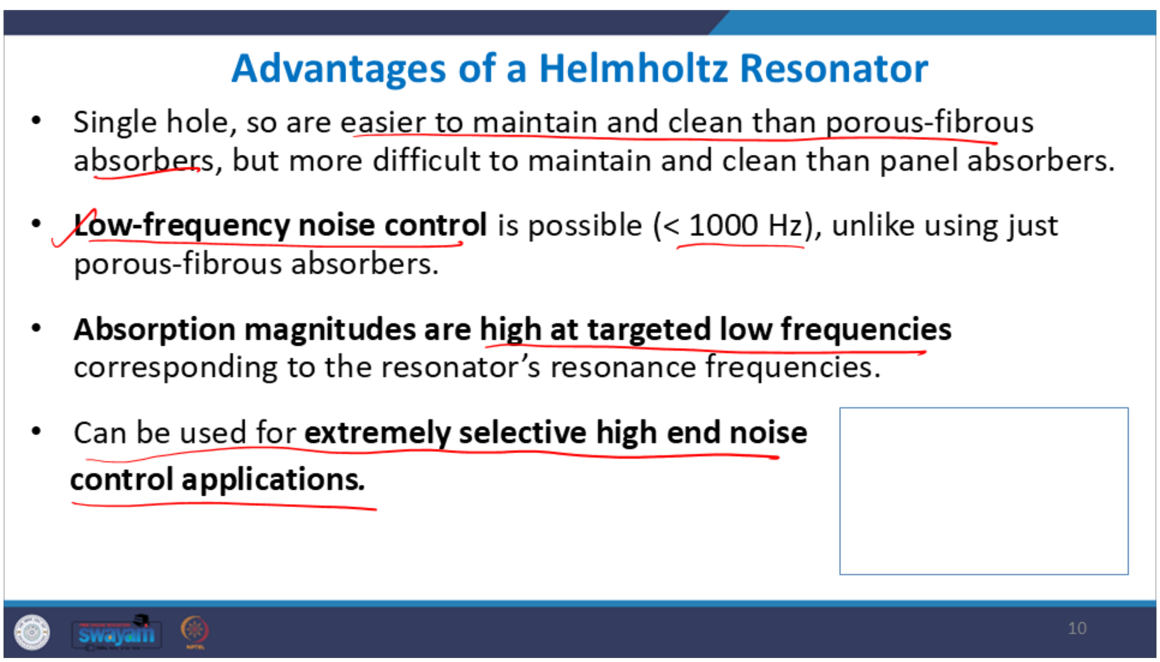
I am writing everything in the SI unit. The radius is okay. So, if you evaluate this expression, what you will find is that it comes close to 1100 Hertz. And you can see this is the sort of absorption characteristic of this resonator, measured. It always peaks.

So, the peak here comes somewhere around 1200 or something in the experimental measurement. So, obviously there are some inaccuracies in manufacturing or, most likely, the inaccuracies in the manufacturing, but it is coming very close to 1100 Hertz, which is the theoretical estimate of its fundamental frequency. So, you can see how the absorption characteristics are very sharp and narrow. Okay. So, suppose from this the first guess you can make is, where can we use this resonator? We can use it, suppose that we have certain machinery which has some kind of a rotating component, and it creates sounds corresponding to the rotational frequency of that component.

So, in that particular frequency and its harmonics, we are getting peaks in the sound wave of the machinery. So, when there are targeted sound peaks, Okay, we know that the sound is occurring at some particular peak. So, when you have tonal sounds, tonal noise sources, or noise sources corresponding primarily to a rotating component of machinery, the waveform will be peaking at certain specific frequencies and their integral multiples. So, when you have such targeted absorption, it is not a broadband kind of sound, but it is more tonal in nature with harmonics.

a very harmonic kind of a sound, then there when we know, we already know beforehand what are the frequencies, what are those specific values of frequencies that needs to be absorbed from the noise waveform, there we can use this resonator. We can design the dimensions of the resonator so that it absorbs the sound exactly at those frequencies.

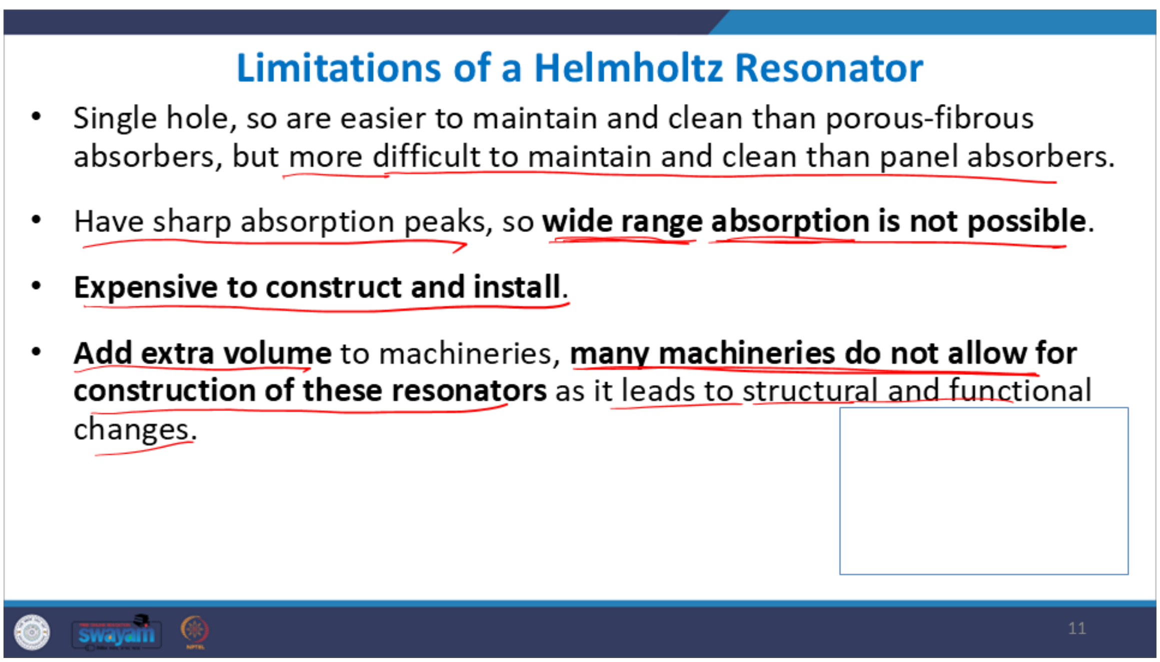
So, let us see the advantages and the disadvantages. So, advantages, you know, it contains a single hole, it unlike porous fibrous absorber, you know it's much easier to maintain because they are not numerous pores and holes so much easier to maintain and clean similarly the fibers there are no loose fibers which will be falling down so again more durable



and more easier to maintain and clean than the porous fibrous absorbers but definitely they are in comparison easier to maintain and clean than the porous fibrous absorbers but more difficult to maintain and clean compared to the panel absorbers because in the panel absorbers you just have a stiff panel you don't have any neck which is a sensitive area and with a you know small dimension or a micro hole or something so it is Easier than porous fibrous, but difficult than panel absorber in terms of maintenance and cleaning. Then low frequency noise control is definitely possible. Okay. These are some of the advantages.

And unlike the porous fibrous absorbers, they can absorb at any kind of low frequency range. And the magnitudes would be very high at the targeted low frequencies. Okay. Most of the times it is almost close to unity. And it can be used for extremely selective high-end noise control applications.

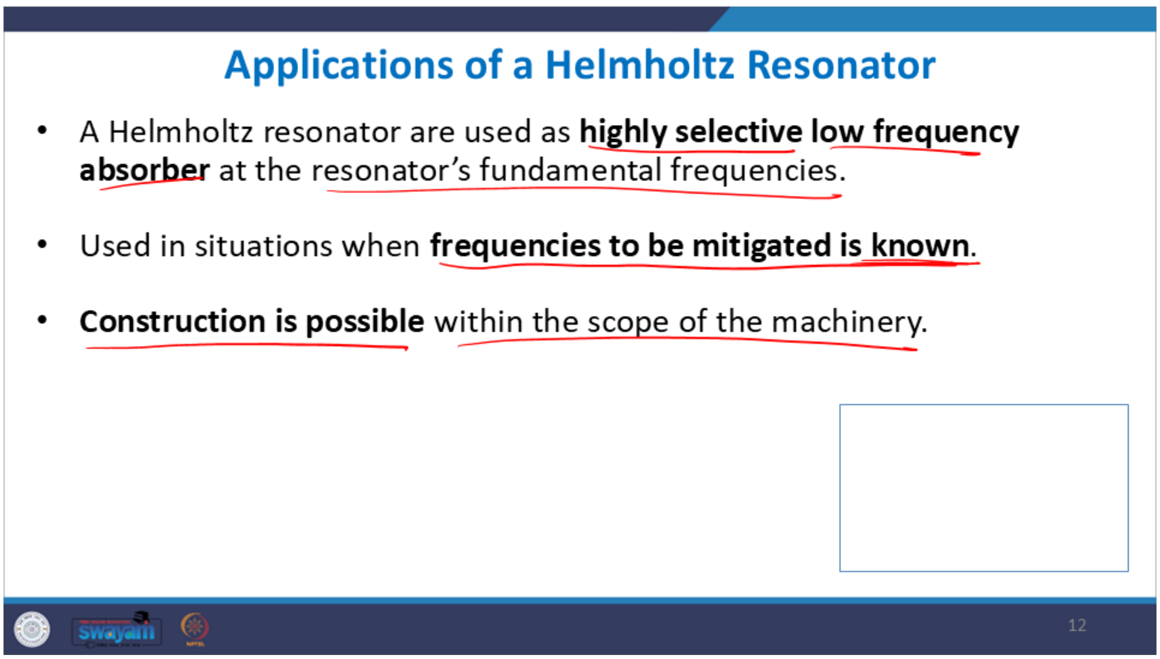
What are the limitations? Again, although they are easier to maintain and clean than porous fibers, but they are more difficult to clean than the panel absorbers. And the very, you know, critical limitation, you know, which really bugs the noise control engineers is that it has got extremely sharp absorption peaks. So, wide range absorption is not possible.



So, this kind of limits its usage. We can only use it for those kind of sound sources where the noise is peaking at some specific frequencies. There is no broadband content in the sound because it can only do this selective absorption like pinpointing and doing the selective absorption at some specific frequency values. okay so wide range absorption is definitely not possible because of the very sharp peak and it is expensive to construct and install in a machinery it adds an extra volume to the machineries and many machineries where you know the the design of the machinery is of prime importance which sort of dictates the function of the machinery there it's not always possible the designer of the machinery will not always allow you that okay in my machinery you can add an extra volume and create some kind of protuberance which can act as a resonator.

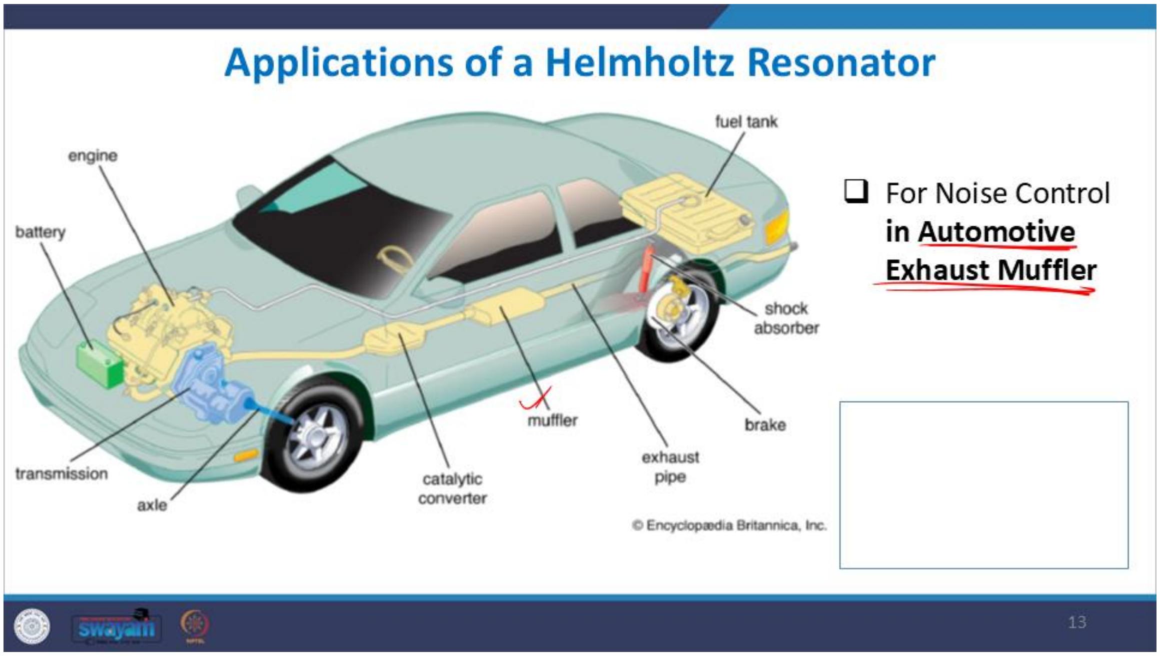
So, not every machinery design can allow for a construction of a Helmholtz resonator. So, again limiting their usage or installation giving an installation difficulty.

So, now, let us see what are the most common applications of these Helmholtz resonator you. So, as I told you that again and again this is a very highly selective low frequency absorber where you know that exactly this hertz you want to absorb.



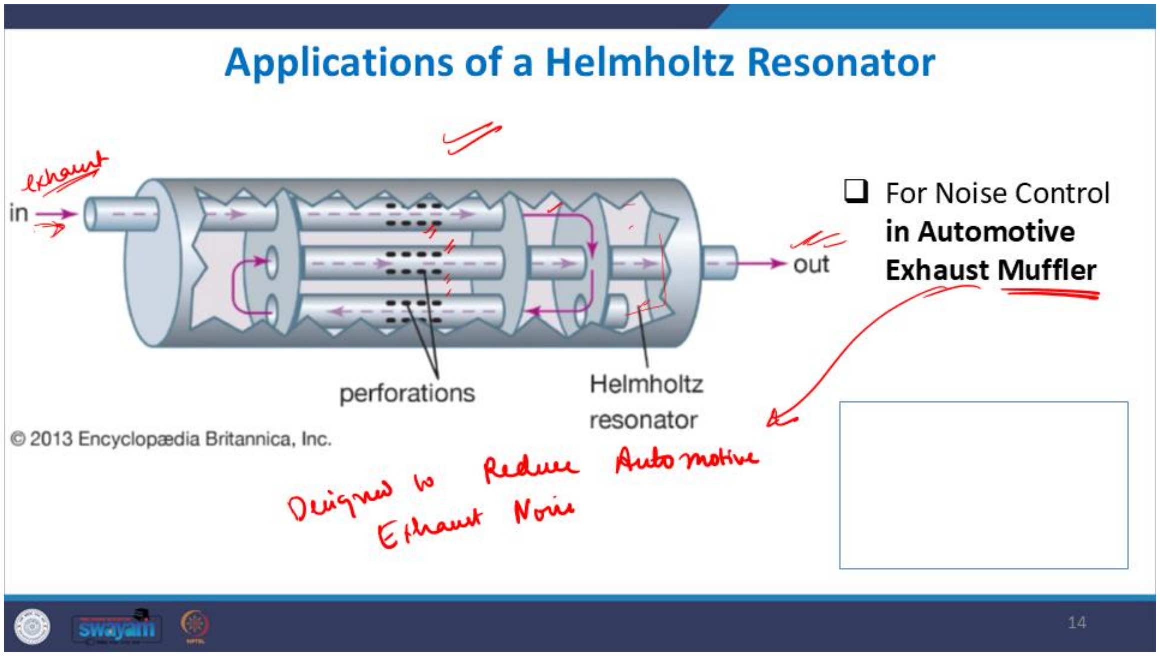
So, 150 hertz or 200 hertz. So, exactly know that that is the value where the sound is speaking and that is the value where I want to absorb. I am not concerned about absorption at a broad range, but only at these specific values and at the low frequency range, then definitely this can act as a very good option. So, it is used in the situations where the frequencies that have to be mitigated are already known to us and where the construction is also possible within the scope of the machinery.

So, let us see I think the most common application of a Helmholtz resonator is as within the you know automotive exhaust muffler. So, you have the muffler built which is built to reduce the you know noise from the exhaust line of an automotive. You know that you know the exhaust is one of the major source of automotive noise. And the mufflers or the silencers are built to reduce this you know exhaust noise. And the resonance almost every these days there is no muffler which is built without a Helmholtz resonator.



A Helmholtz resonator is there in every modern automotive exhaust muffler. So, it is very widely used in this application. So, what is the purpose to reduce the exhaust noise? You can see here in this vehicle you know. the muffler is there in the tail pipe or the pathway of the exhaust.

And what it does? So, if you see here, so you know that you know the exhaust is coming out, the exhaust noise it will depend on how the engine of the automotive is functioning. And engine is a very classical example you know engine it has its own unique cycle ok. It has got a typical RPM at which the engine is running and based on the RPM or the revolutions per minute, you can find out what is the cycle frequency in revolutions per second. And you would know that these many times per seconds you would have the release of the exhaust and these many times per second you would have the combustion happening.



So the whole operation of the IC engine within an automotive system it is very synced with the frequency at which the engine is operating. So, here whatever noise is created because of the operations of the engine, be it the combustion noise, be it the exhaust noise or any other thing related to the engine, the waveform, the sound waveform it will be such that the noise will be peaking at some fundamental frequency which will correspond to the frequency at which the engine is operating. So, the sound will peak at the engine frequency and its higher harmonics. So, it is a very classical example. The engine noise, whatever is the engine noise or the exhaust noise, it has a typical harmonic content.

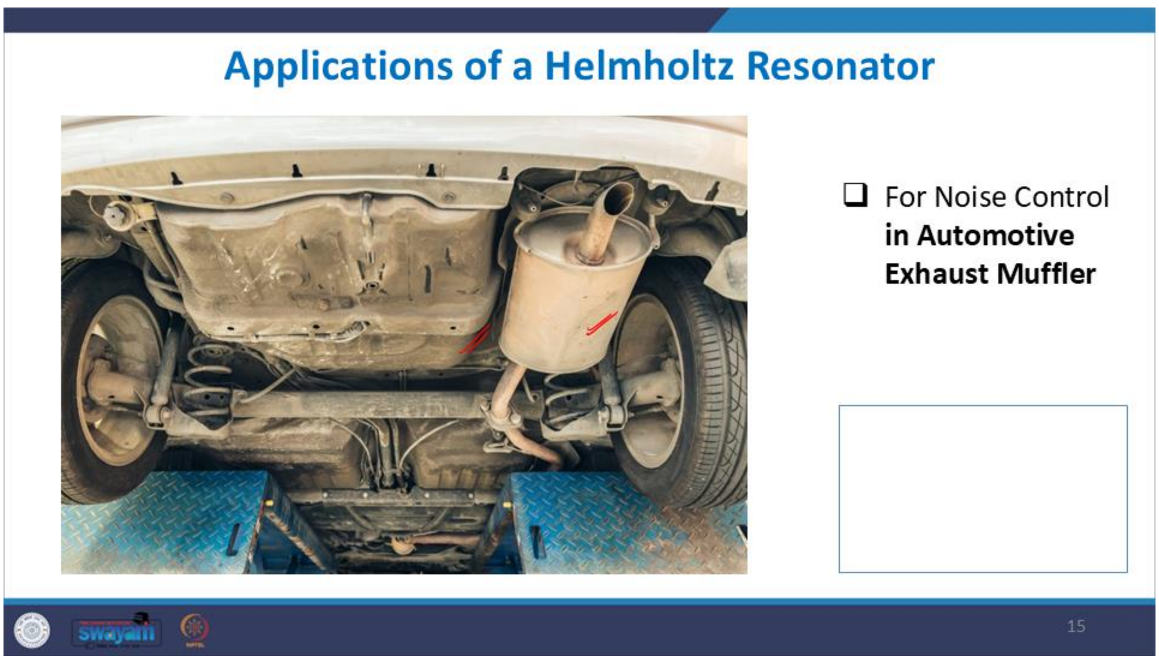
It peaks at a fundamental frequency and its higher harmonics. So, that becomes the best candidate for a Helmholtz resonator to absorb. So we can create a Helmholtz resonator whose fundamental frequency is going to match with the fundamental frequency of the exhaust noise waveform and it will absorb those frequency components. So this shows a typical you know automotive muffler the exhaust you know is going in into this muffler. So, this is designed to silence or reduce the exhaust noise, okay.

So, a muffler is designed to reduce automotive exhaust noise, and a Helmholtz resonator is incorporated in every modern exhaust muffler, okay? This muffler here. This is what it does. And so, the exhaust air comes in through this pipe. It passes through these perforations. As you can see, this is the pathway it is following.

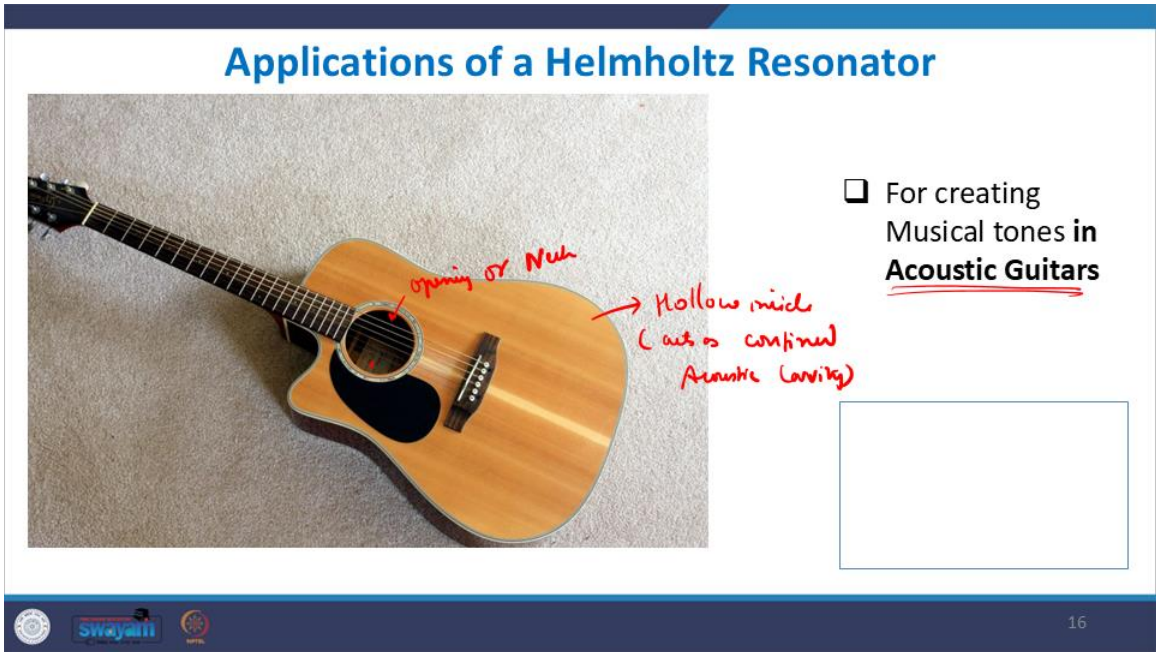
If you follow this arrow here, it goes here. Then after that, it comes to this cavity. Then it goes here and here, and finally, it goes out through this way. So, this is how it follows if you follow this arrow. So, first of all, some kind of noise loss happens because it is passing through these perforations, and in the perforations, there are viscous losses happening.

In our next lectures, we will study perforated panels and micro-perforated panels. So, you will learn in detail how small holes—how just making some sound waves pass through these small holes—can actually lead to attenuation of the sound. So, first of all, the exhaust is made to pass through these perforations, and some loss is happening. While passing, they enter this cavity space. This becomes your Helmholtz resonator, and then it absorbs.

So, while the exhaust air is passing through it, There is, at the side of the pathway of the exhaust, a Helmholtz resonator which absorbs the various harmonics, and after passing through this, it comes out. This shows the back view of a car, and you can see this kind of muffler, which has a Helmholtz resonator built within it.

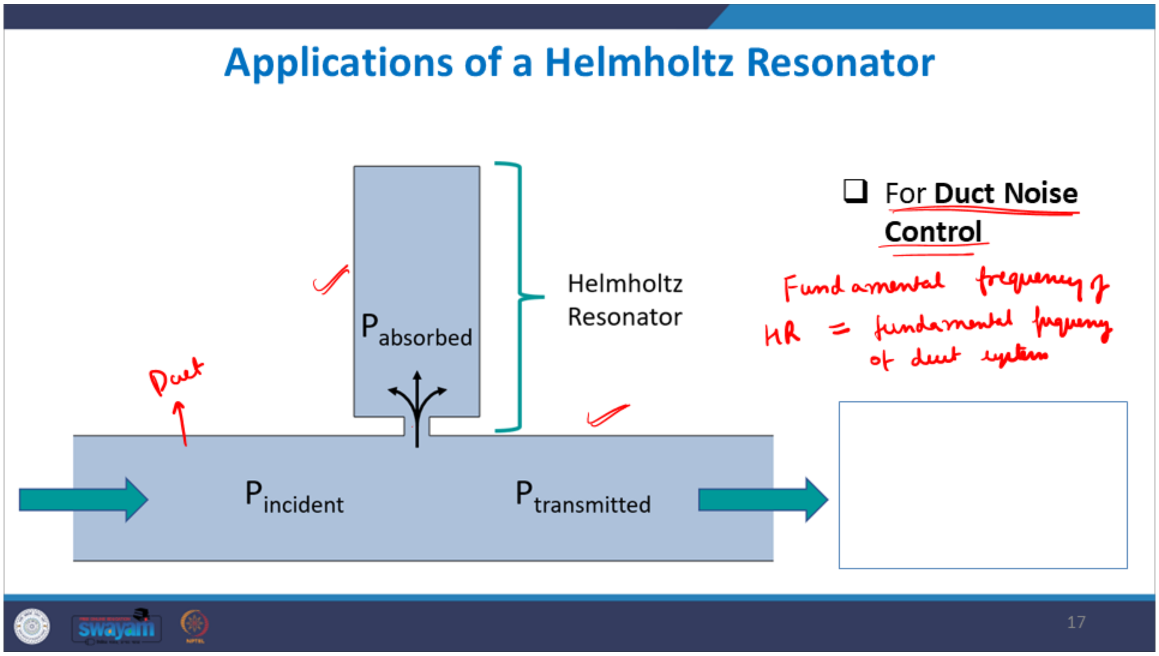


Another application is simply to create musical tones in various kinds of instruments, such as acoustic guitars. Here, you can see this becomes the opening, and this is the wooden structure, which is hollow inside, right? This is hollow inside.



So, this acts as a confined acoustic cavity. The wooden box is the rigid boundary, and within that, we have the confined acoustic cavity. This is the opening of the cavity, or the neck, and this itself is a Helmholtz resonator. So, when we pluck the strings of the guitar, it creates a vibrational motion or an oscillatory motion, which hits the opening of the cavity, or the neck, and then it acts as a Helmholtz resonator and tunes with the vibrations at its resonant frequencies, which creates very tonal sounds. Okay.

In the same way, it can be used for various duct noise controls. You know, ducts and piping systems in various industrial machineries carry various kinds of fluids at various temperatures.



So, first of all, there is noise due to the flow of the fluid itself, and then there is noise due to the vibrations of the pipes. So, these ducts and pipes are major noise sources in various kinds of machinery. And what you can do is, usually, Helmholtz resonators are built as a side branch in the duct system. This is a typical schematic of how a Helmholtz resonator is built into a duct. This is your duct or pipeline, and then on the side, you have this protuberance or cavity built up, which is the Helmholtz resonator, and it is used to absorb the duct noise.

Here also. The design is such that the fundamental frequency of the Helmholtz resonator that is built should match with the fundamental frequency of the duct. The duct is an open pipe; it will have its own fundamental frequency, so the fundamental frequency of the duct system. So, at those frequencies, the highest amount of noise will be created while the fluid is flowing through the duct. So, the noise in the duct will peak at its natural frequencies, and that should match with the fundamental frequency of the Helmholtz resonator so that at those frequencies it can absorb the maximum sound.

This shows a typical pipeline in steel machinery, and this kind of structure is actually the Helmholtz resonator within this. Okay.

Applications of a Helmholtz Resonator

- For **Duct Noise Control**

So, with this, I would like to close this lecture. Thank you for listening.

Thank You