**NOISE CONTROL IN MECHANICAL SYSTEMS**

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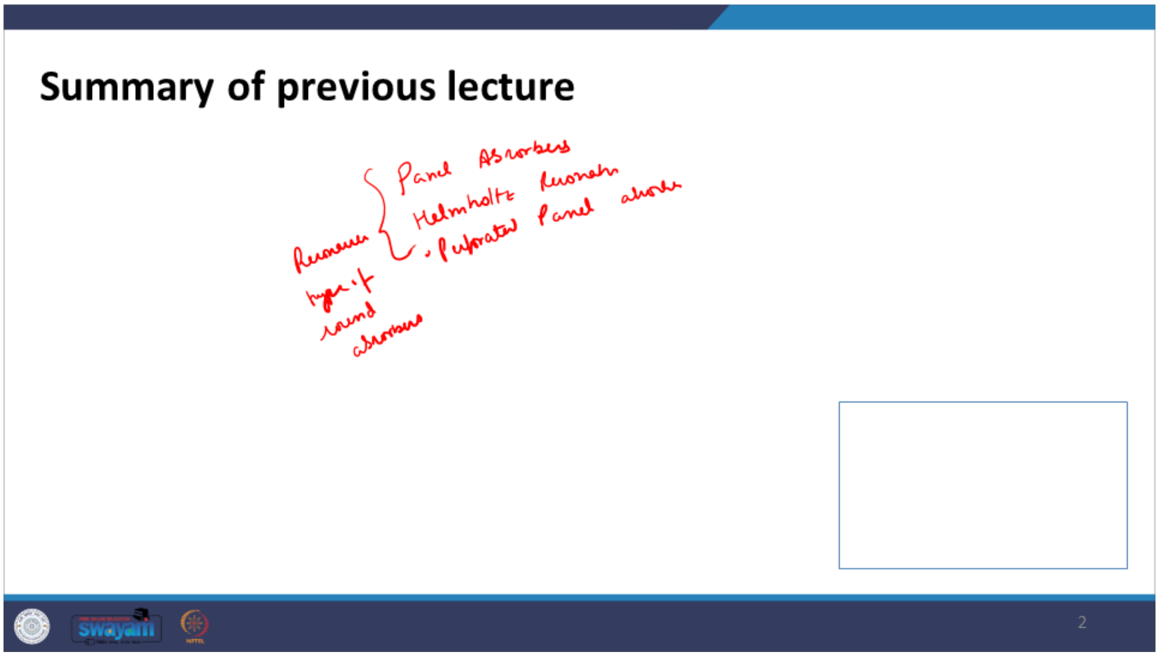
**Week:9**

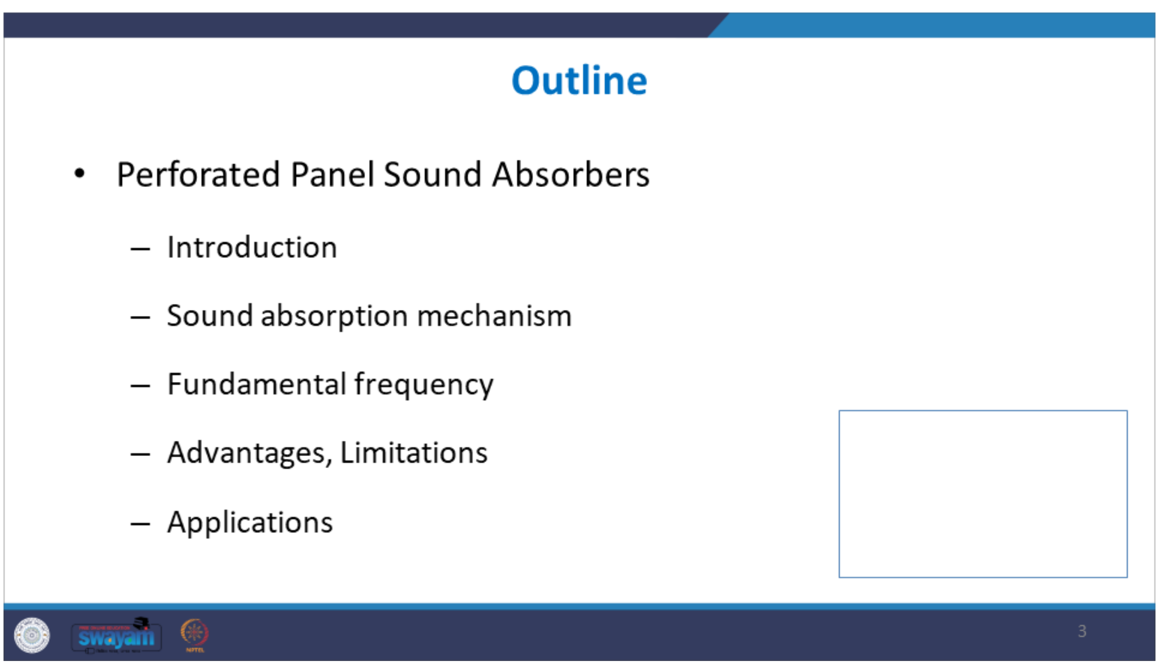
**Lecture:42**

# Lecture 42: Perforated Panel Sound Absorbers

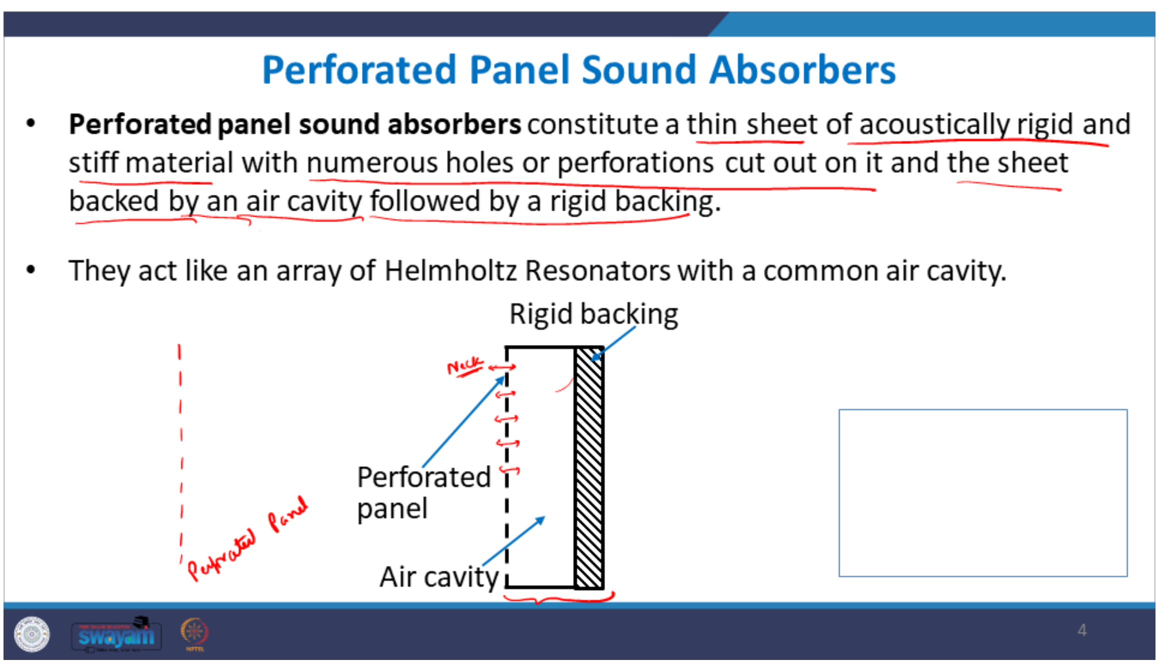

Hello and welcome to this lecture series on noise control in mechanical systems with me, Professor Sneha Singh from IIT Roorkee. In today's lecture, we will start with a new kind of sound absorber, which is a perforated panel sound absorber. So far, we have discussed panel absorbers and Helmholtz resonators. These were the resonance type of sound absorbers because the main mechanism behind them is the resonance phenomenon. One more type of this is a perforated panel absorber, which we will discuss today. This is a new type within that.




So, the introduction, the absorption mechanism, the fundamental frequency, and the advantages, limitations, and applications of this absorber will be discussed.

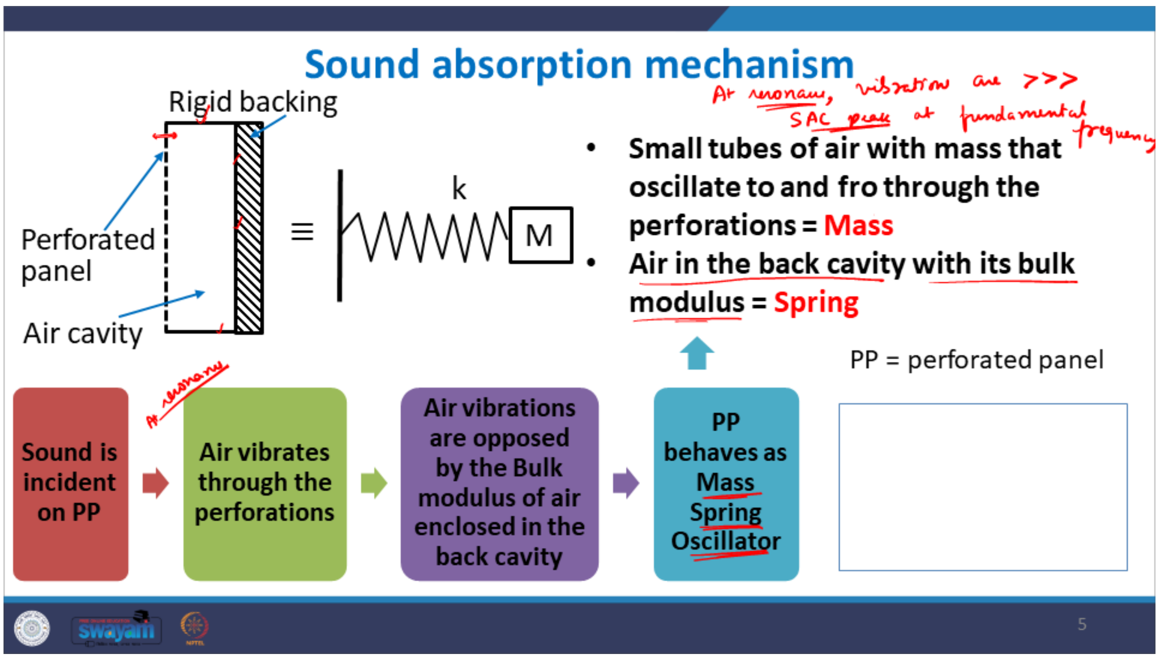


So, what is a perforated panel sound absorber? It is very similar to a panel sound absorber, but it constitutes numerous holes or perforations cut out on it. So, it has a thin sheet of some acoustically rigid and stiff material. This means that when sound is incident on it, the panel should be rigid; it should not undergo longitudinal vibrations, so it remains rigid and stiff. The only way for the sound to enter and vibrate through is through the holes or the perforations which are cut out in this panel, okay? Behind the thin sheet or the perforated panel is an air cavity followed by a rigid backing, okay? So, this is a typical configuration of a full perforated panel. In many cases, you just have perforated panels like this single one, okay? This is also a perforated panel absorber. In many cases, because they are absorbers, they will make the sound waves pass through them, but they are more effective when they are enclosed, when they have a confined air cavity in between just behind them with a rigid backing. This is how it looks like. As you can see, this perforated panel is an extension to the concept of Helmholtz resonator that we have just discussed. Here, they act like an array of Helmholtz resonators with a common air cavity. As you can see, this can constitute a thin neck through which the sound wave is vibrating. This becomes the neck of that Helmholtz resonator, followed by a confined air cavity behind it with a rigid backing. And like this, you have so many such necks or periodic combinations of these necks. So, it becomes like an array of Helmholtz resonators.

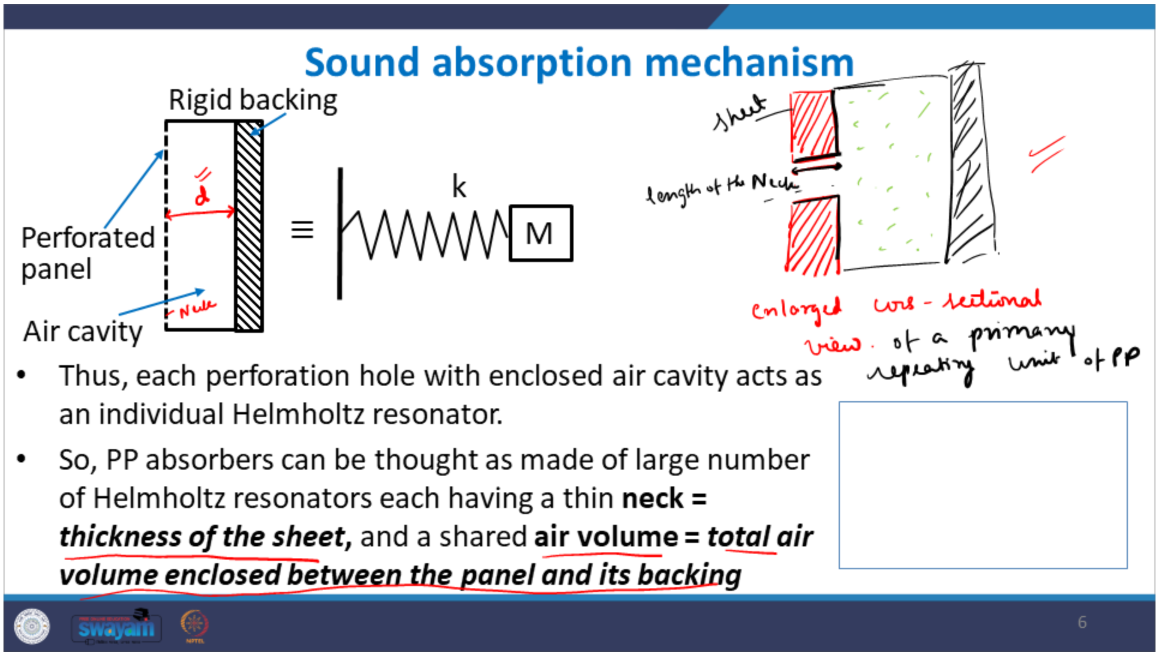


So, what is the sound absorption mechanism? The sound is incident on this perforated panel, and air vibrates through the perforation. So, remember that the sound is incident on the perforated panel, and at the resonance frequency, what happens? The sound waves are able to enter through inside, and at resonance, This happens: air vibrates through the perforations. The air vibrations are opposed by the bulk modulus of the air that is enclosed inside the back cavity because the air is confined from all sides, and then there are some sound waves. Due to the incidence of the sound waves, the air molecules through these perforations are set into back-and-forth motion. Then, they try to compress or expand the confined air cavity, and because of the inherent bulk modulus, the confined air cavity resists it because the air cannot just escape around. Okay, it's bounded from all three sides, okay. So, it cannot just move around. The particles cannot just move around to accommodate these longitudinal vibrations that are impinging on it, and hence they oppose. So, they have to accommodate it; they have to compress and expand. With respect to the longitudinal vibrations. So, suppose this is how the particles are vibrating, and they are hitting these confined air molecules. So, whenever they are going into this motion, the air particle has to compress the confined air cavity, and when they go into this motion within the neck, the confined air cavity to accommodate then expand. So, it can lead to the expansion and compression of the air particles within the confined cavity, and because of its inherent bulk modulus, it is going to oppose this. So, just like the concept of a Helmholtz resonator—I will not repeat it again in detail—but now it becomes the same thing, you know, like an air-spring oscillator. So, it behaves like an air mass-spring oscillator system. So, what is the mass?

The small tubes of air. with mass that oscillates to and fro through the perforations. Those act as the mass because they are the mass that is sort of vibrating. So, this is the mass of these small tubes of air, which are oscillating to and fro through the perforations. And, the spring here—which is opposing this motion—is due to the inherent compressibility of the confined air cavity. So, here the air, which is confined within the back cavity with its bulk modulus, acts as a spring element that is trying to restore this motion. And, hence, the resonator is set into vibration. And because it is a resonator, it can be viewed as a typical mass-spring oscillator. It will have its own unique fundamental frequency, and when the phenomenon of resonance occurs at the fundamental frequency, the absorption is going to be the maximum because the vibrations and all the other phenomena are going to amplify much larger in magnitude. So, at resonance, the vibrations are much greater, and hence the acoustic coupling happens. Whatever sound energy is able to enter the absorber, the incident sound energy is then used up in vibrating these particles and setting them into resonance. So, the SAC peak can be observed at the resonance frequency. Or at the fundamental frequency of this particular mass-spring oscillator. So, hence in the absorption mechanism, say the absorption response, the fundamental frequency is very important.

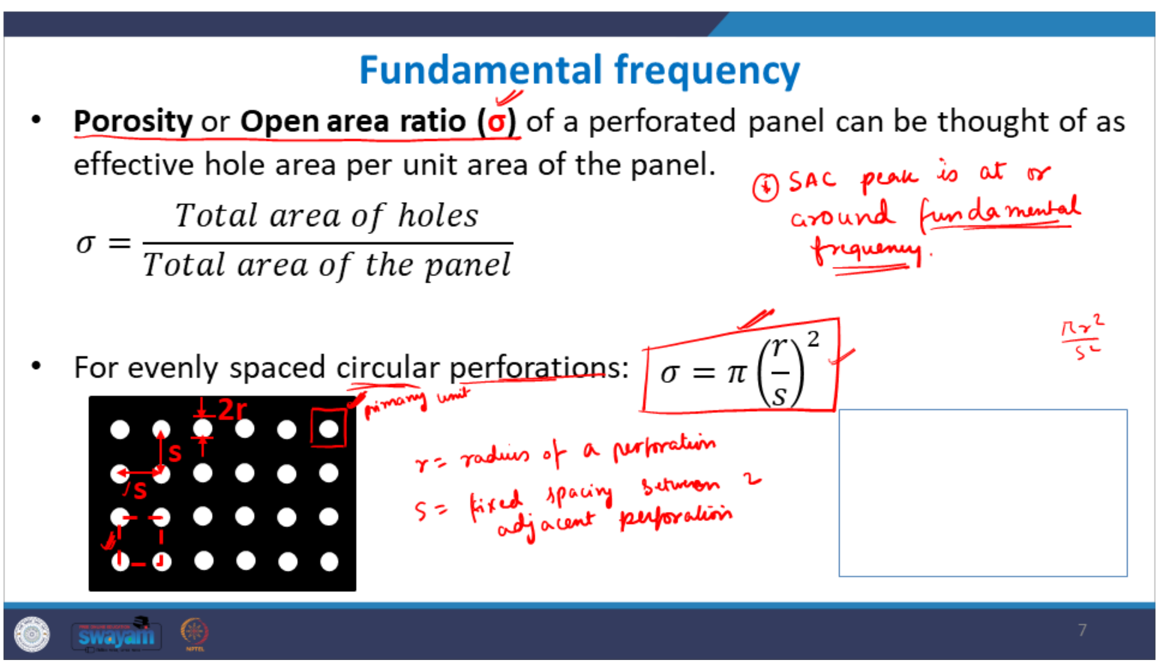



So, here, you know, because now it is acting as a Helmholtz resonator. So, a large number of Helmholtz resonators can be thought of as made of this, and here the neck is the thickness of the sheet. Ok. This thing here is your neck for the Helmholtz resonator, and the air volume is that volume of the air which is being enclosed with a rigid backing.




So, let us derive because, you know, the SAC response depends a lot on the fundamental frequencies. I said that the SAC peak is at or around the fundamental frequency, and this is not just for this absorber but for, you know, most of the absorbers—all kinds of resonance-based absorbers like the Helmholtz resonator, the panel absorber, the perforated panel absorber, and later we will study about the micro-perforated panel absorber. So, in all these four types of resonance absorbers, the fundamental frequency is very important because the main phenomenon of sound energy dissipation is that the incident sound energy or the incident noise should be able to set the resonator into resonance vibrations. It should be able to set the resonator into high-amplitude vibrations, and the incident sound energy then gets used up or gets dissipated in order to do the work in setting it into vibration. So, at resonance, you have maximum absorption. So, the fundamental frequency becomes very important because that is the frequency where the incident frequency matches the fundamental frequency, resulting in the resonance phenomenon, and hence we observe a peak. So, for all of these resonator absorbers, we are deriving the fundamental frequency. So, we have already seen what the fundamental frequency of a single Helmholtz resonator is. Now, here it is like an array of Helmholtz resonators. So, we will use that concept and find out its fundamental frequency. So, for this perforated panel, one important terminology that is usually used to define its sound absorption performance is the porosity, sigma. Sometimes it is also called the open area ratio. So, it can be thought of as an effective hole area per unit area of the panel. So, you can say that per unit area of the panel, how much proportion or fraction of the per unit area is actually the perforation or the hole. So, for the overall panel, it becomes the total area of holes divided by the total area of the panel, and suppose we imagine one repetitive unit like this. Either we can imagine one repetitive unit like this or we can imagine one repetitive unit like this—either way—and then we can think of this perforated panel resonator as a repetition of this unit cell or this unit. This is the primary unit which is getting repeated. To make a large perforated panel. So, if we observe just this primary unit which makes up this panel. So, either we can observe this one or we can observe this and find out its porosity, then we would be able to define the porosity for a large sheet of perforated panel. So, this is for circular perforations, ok. So, if r is the radius of the hole and s is the spacing between the holes, ok. This is the radius of a perforation, and given that all perforations are uniform in dimensions and that the spacings between the perforations are also constant. This is fixed; it is not varying here, so fixed spacing between any two adjacent perforations. So, in that case, the porosity, as you can see for 1 unit, the total surface area of a repetitive unit is s. It is a square of side s. So, s square becomes the total area of the unit, and the hole area is the area of that single circle of radius r, which becomes $\pi r^2$. So, what you would get is $\pi r^2$ divided by $s^2$. So, ultimately, this is your formulation for the porosity of this panel.

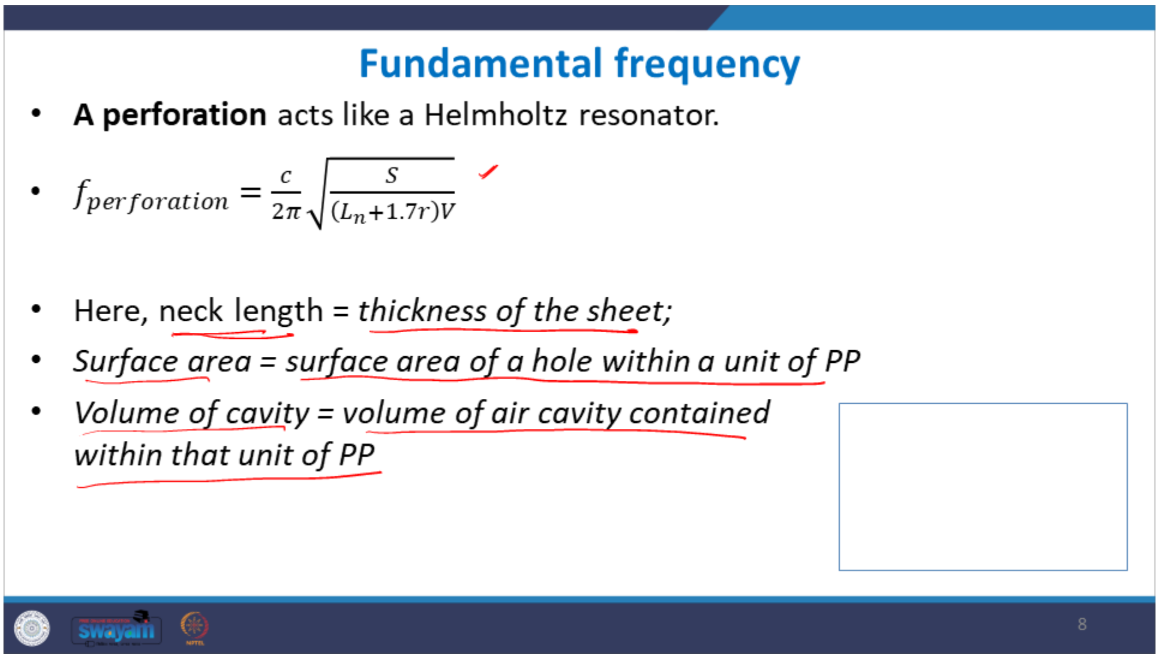
$$\boldsymbol{\sigma = \frac{\pi r^2}{s^2}}$$



So, now, we know that each perforation acts as a Helmholtz resonator. Therefore, in terms of Helmholtz resonator, the perforation fundamental frequency can be given by this formulation,

$$f_{perforation} = \frac{c}{2\pi}\sqrt{\frac{S}{(L_n+1.7r)V}}$$

where S is the surface area of the neck. The opening in the neck, l is the length of the neck, v is the volume of the confined cavity, and r again is the radius of the neck, okay. So here we know that in this case, our neck is what? It is the thickness of the sheet. The sheet itself acts as a neck, okay. So suppose this is your perforated panel. I'll draw one enlarged view where this is your solid material and then you have some perforation. So, this is an enlarged cross-sectional view, okay. Okay, this is one perforation. So, as you can see this distance here is the this acts like a neck okay for the cavity And then you have some confined cavity here, confined like this. So, here this acts as the neck, okay? And what is this? This is the sheet. This is actually the sheet which is making up the perforated panel. So, here the thickness of the sheet becomes the length of the neck, okay? So, this becomes the length of of the neck because here this becomes your sheet. So, the thickness of the sheet here where the sound waves are entering it becomes it acts as the length of neck for an equivalent Helmholtz resonator and the volume of the air cavity is simply for this is for a enlarged cross sectional view of a primary repeating unit of a perforated panel. So, in this, the volume of the air cavity then is simply, it is the volume behind, the volume behind or the volume of the air cavity just behind that repeating unit, okay. That will make up the volume of the confined and then you will, so for each perforation this becomes our formulation, it acts like a Helmholtz resonator, so the effective volume is You can simply calculate the things for a single, you know, primary repetitive unit and then you can get the expression for an infinite panel because the same thing happens, okay. Sound absorption is a per unit area property. So, we can observe it for a unit repeating area of the perforated panel and then we can sort of extend it in the two dimensions to as much as we want and we will get the same sound absorption okay. So, just we can see the sound absorption for a single repeating unit of a perforated panel. So, we already see the porosity for that repeating unit and this is our formulation for the Helmholtz resonator. So, here the neck length for that repeating unit is simply the thickness of the sheet The surface area then becomes because the air is entering through a perforated hole okay a circular perforated hole and the air is entering inside the cavity so that hole is the opening of the neck. So, the surface area of the neck would be the surface area of the hole within a single unit of PP or the perforated panel and the volume of cavity is what? It is the volume of air cavity which is contained within that particular unit of the perforated panel as already explained here with this kind of analogy. So, let us put those quantities and see what is the fundamental frequency we get. okay.



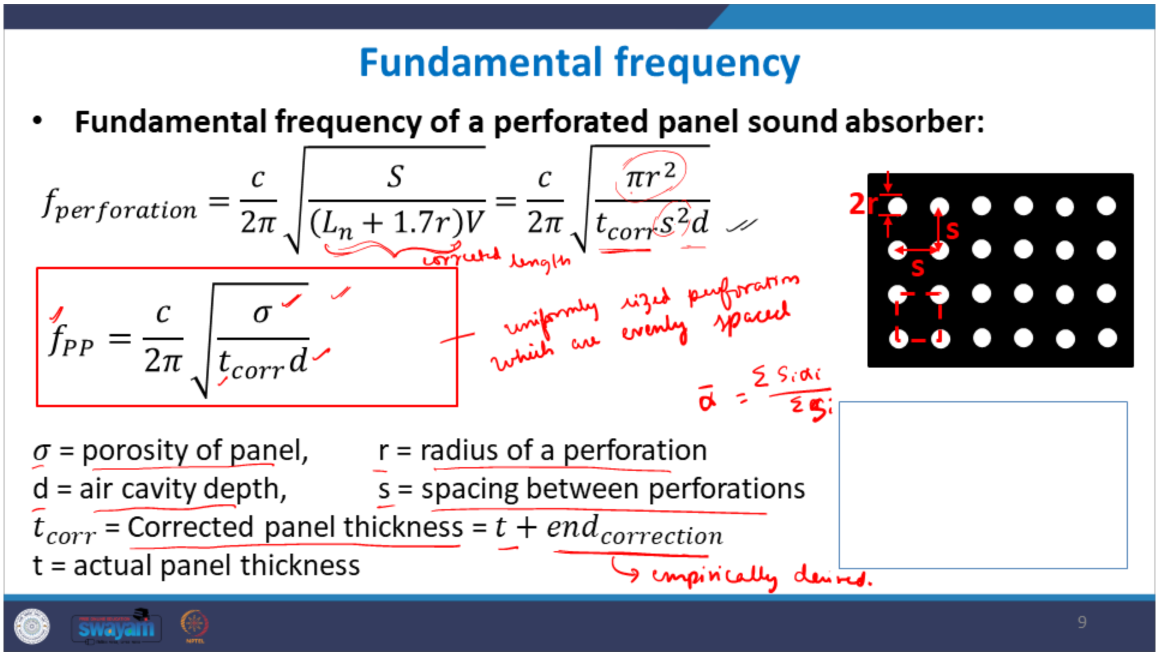

So, now we have put the surface area S becomes the surface area of the neck which is same as the surface area of the perforated hole which is $\pi r^2$. So, this is like the corrected neck length okay. This is like the corrected neck length which is the neck length plus 1.7 times r. This is an empirically derived relationship from various experimental studies. So, which means that Length plus some correction factor we are adding to get a corrected length for the neck.

$$f_{perforation} = \frac{c}{2\pi}\sqrt{\frac{S}{(L_n + 1.7r)V}} = \frac{c}{2\pi}\sqrt{\frac{\pi r^2}{t_{corr} s^2 d}}$$

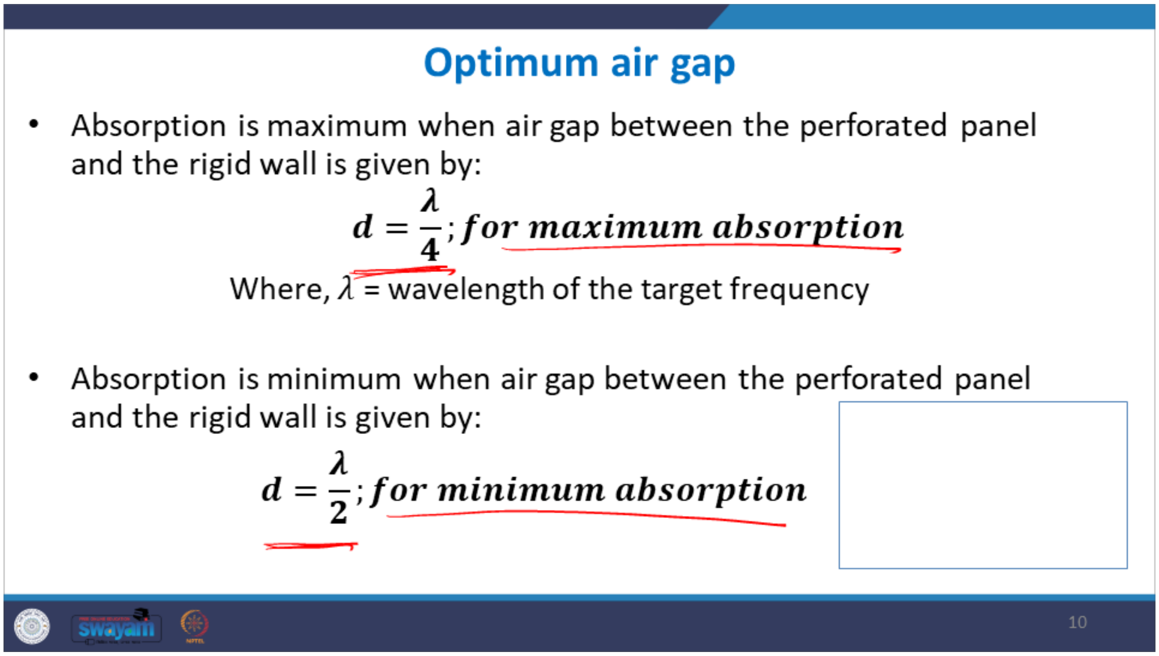
So, we can simply add the corrected thickness of the sheet in place of this corrected neck length. And the volume of the cavity would be the volume of the cavity just behind the repeating unit. The surface area is S into S, so $S^2$, and the depth of the cavity is d. So, in this figure here, you can take this as the d or the depth of the cavity. Then, S squared multiplied by d is going to give you the net volume of the air cavity contained within it, okay. So, you put this S squared into d. So, ultimately, what you get is this term here: $\pi r^2$ by $S^2$ is what? This was simply defined as the porosity: $\pi r^2$ by $S^2$, okay. So, this $\pi r^2$ by $S^2$, this term here, now can be replaced by simply the porosity of the panel, which is sigma, divided by the corrected thickness of the sheet and the depth of the air cavity. So, c by 2 π under the root of this term will give you the fundamental frequency of the perforated panel, where this is the definition of the various parameters.

$$f_{PP} = \frac{c}{2\pi}\sqrt{\frac{\sigma}{t_{corr}d}}$$

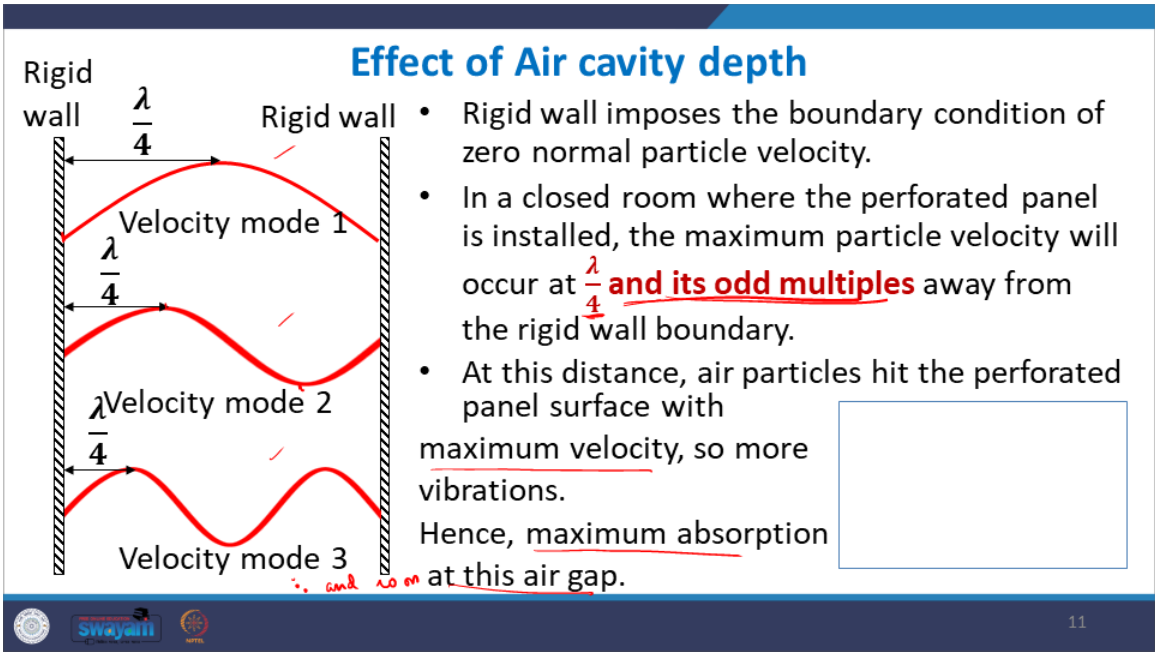
σ is the porosity of the panel; r is the radius of a perforation. So, this is for uniformly sized perforations, okay, each perforation. Perforations which are evenly spaced. So, that is why we are able to define for the entire sheet using a single repeating unit, because the perforations throughout are of uniform size and they are evenly spaced. If there was some kind of gradation or some kind of, you know, changes in the size of perforations, as well as changes in the spacing across the area of the panel.Then what would happen? It would act as a composite kind of absorber. You can derive separately for the different areas having uniform-sized perforation and uniform-sized spacing, and then you can use that formulation, you know. This formulation that we use to get the overall absorption coefficient for that panel. So, you first find out individually for the uniform areas within the perforated panel, then find out the absorption coefficient, and then you add up like this. So, this particular case is only for the uniformly sized perforations which are evenly spaced. d is the depth of the air cavity, as shown in this figure here. This is your d, the depth of the air cavity or the distance between the sheet and the rigid backing—that is your d. And then, S is the spacing between the perforations, t is a corrected panel thickness which could be t plus some end correction factor, and these all things are empirically derived from experiments. Then, t is the actual panel thickness.



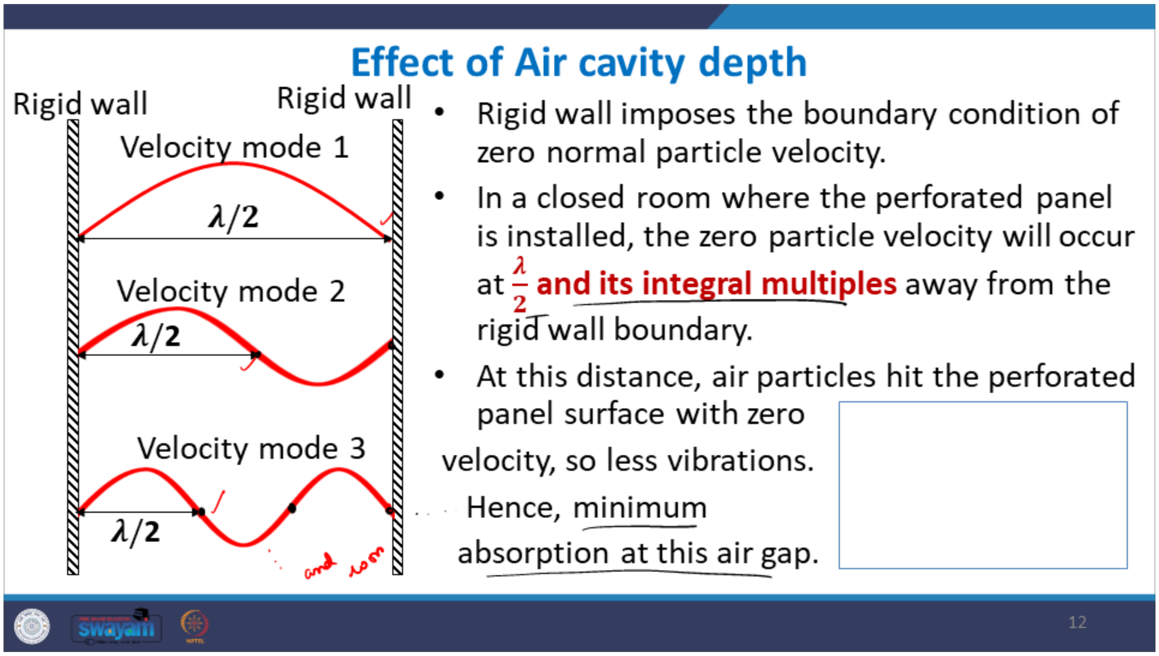

Now, optimum air gap—so what should be the optimum gap between the perforated panel and the rigid wall? Just like how we studied for panel absorbers, in the panel absorbers we saw that at λ by 4, if we keep the panel, if we keep the distance between the panel and the rigid wall of the room as λ by 4, there we have maximum acoustic particle velocity and hence the vibration and the resonance phenomena multiply, and there you can get the maximum absorption. So, a similar concept is used for the perforated panel as well. At λ by 4, you observe maximum absorption, and at d equal to λ by 2, you observe the minimum absorption, okay? Where d is the depth of the air cavity and lambda is the wavelength, so at So, why is d equal to λ by 4?



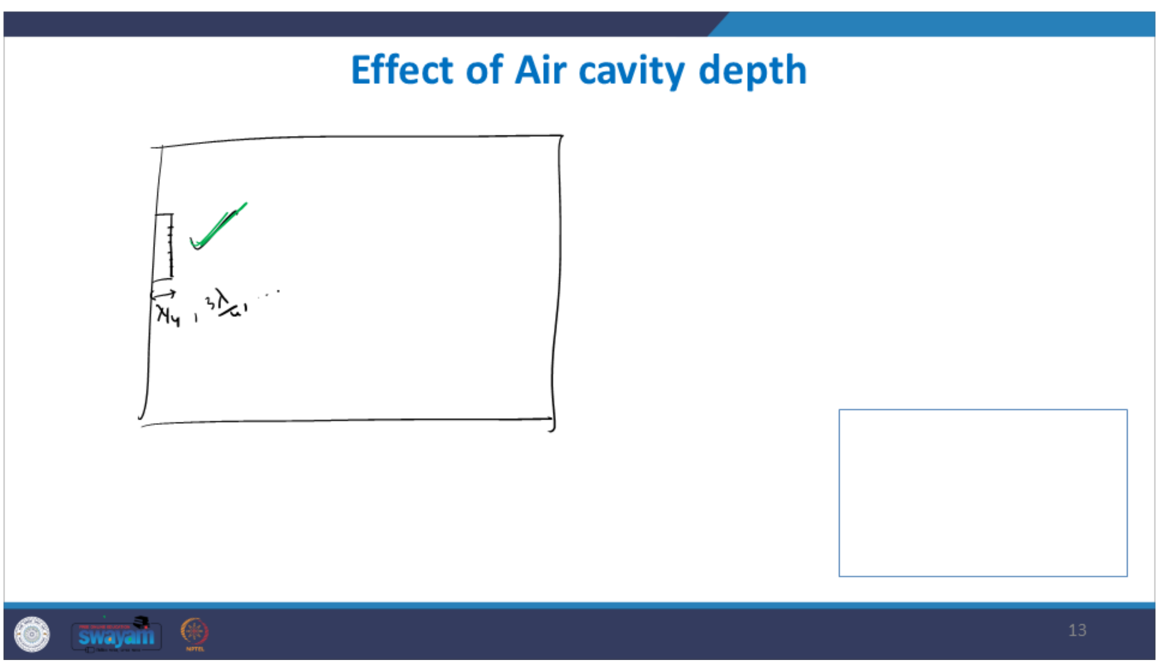

I am trying to recollect what we have studied before. Suppose this is, you know, the rigid wall always imposes the boundary condition of zero normal velocity because once the sound waves encounter a rigid backing or a rigid wall, they cannot impinge and go further. So, their velocity suddenly has to come to a stop. So, it is imposing a zero normal particle velocity. The particles stop moving once they encounter a rigid wall and cannot move further. So, in that case, the typical sound waves or the modes that can exist have these kinds of forms and so on. And so on. But whatever it is, it is always at λ by 4 because here, lambda is where the velocity becomes zero. So, the very first instance when you can observe a maximum velocity would be at λ by 4, and then λ by 4 plus some subsequent, you know, odd multiples, so either here, here, or here. So, at the various crests and troughs of the wave, you will observe that the magnitude of the particle velocity is going to be the highest. So, at λ by 4 and its odd multiples, you will observe this phenomenon, and hence, whenever the depth of the air cavity in a perforated panel is maintained either at λ by 4 or at the odd multiples of λ by 4, there you have the maximum velocity with which the particles of the incident sound waves are hitting, and the entire phenomenon of resonance-based energy losses gets just amplified further, and maximum absorption is obtained. In the same way, because, you know, it depends on what the velocity is with which the particles are sort of entering inside the perforated panel.



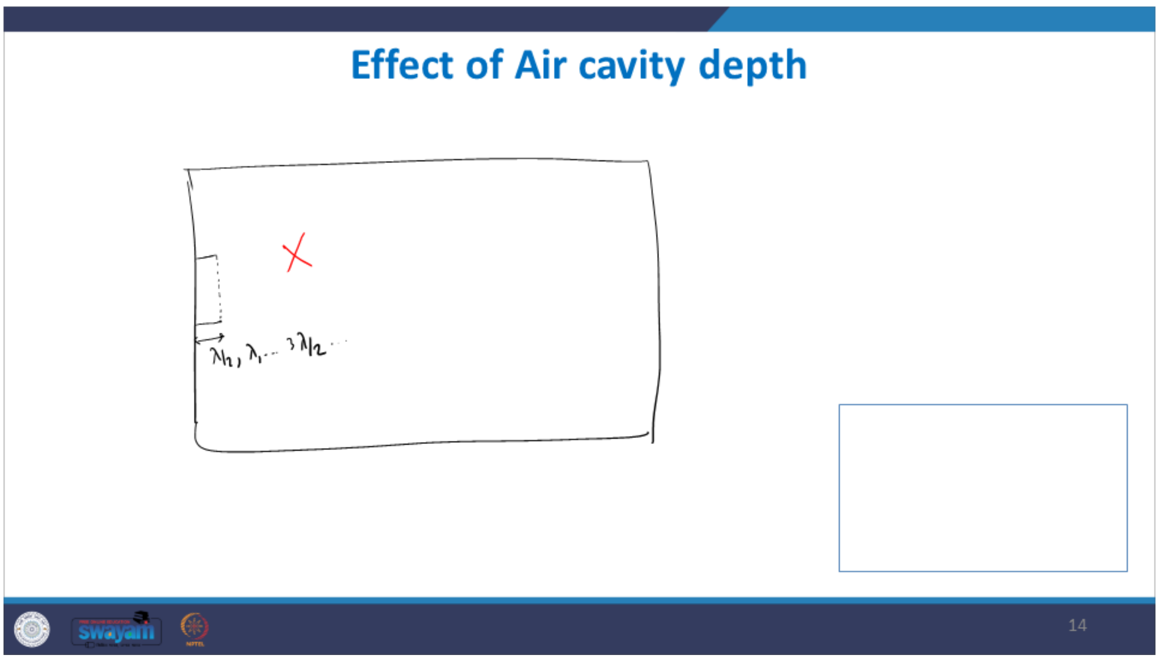

If, suppose, for the same case, at λ by 4 and its odd multiples, you have the maximum magnitude of the acoustic particle velocity, and in the same way, at π by 2 and its integer multiples, you will observe zero velocity, as you can see here: zero velocity here, here, and so on in all the successive you know mode of the waves wherever you have λ by 2 or its multiples. So, here at λ by 2, then at λ, then at 3 λ by 2 and so on at all these places over here, here, here and so on. So, at all these places the particle velocity is becoming 0. So, it is λ by 2 or the integer multiples. So, whenever that depth is maintained then you know the particles they are hitting with the least velocity and hence no matter if it is at the fundamental frequency, but the energy dissipation will not be high because the energy of hitting itself is less ok. So, in that case minimum absorption would be obtained ok. So, here what I want to say here is that the absorption peak happens. So, one confusion I want to erase here is that the absorption happen the peak of the absorption happens at the fundamental frequency of the perforated panel and depending on what is the depth of the cavity, the magnitude of the peak can be high or low. So, you will observe the higher peak when the d is λ by 4 or its odd multiples and you will observe a smaller peak when the d is maintained as lambda by 2 and its integer multiples. The depth of the air cavity will not change the fundamental frequency per se. It will change the fundamental frequency obviously. using this because it is here in this formulation. So, and then based on which how it is related to the λ of the wave, the SAC peak can have a higher magnitude or a lower magnitude at the resonance frequency ok.



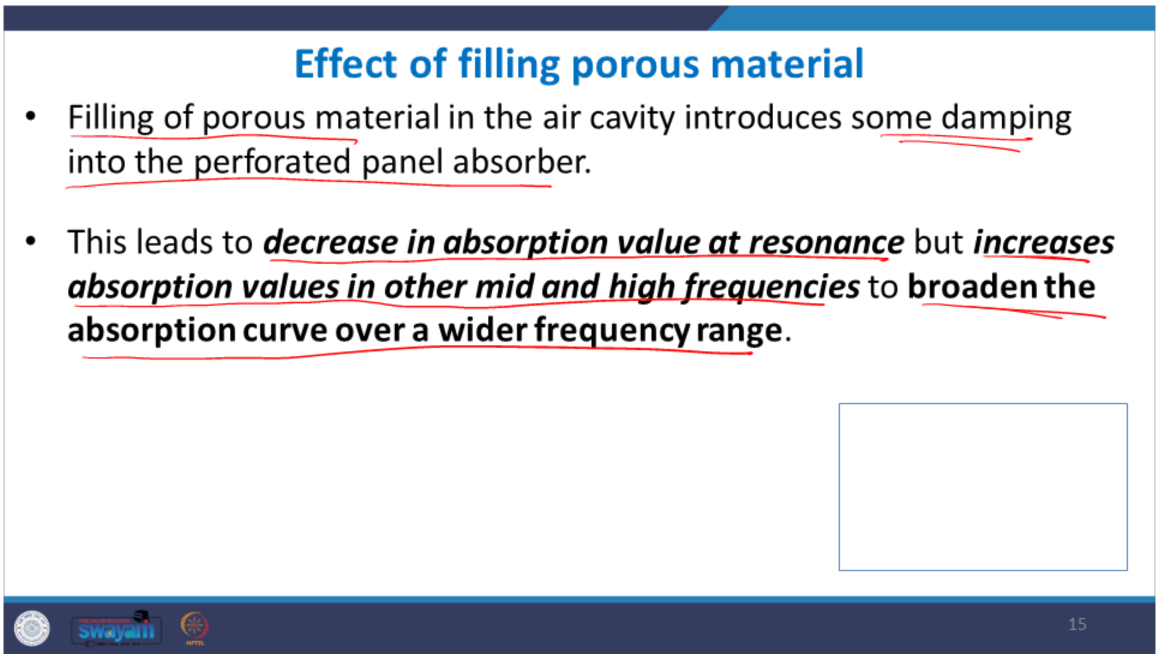

So, suppose we have got some kind of a room, and we want to make a perforated panel and install it. We can install a perforated panel here. So, we can maintain this as λ by 4, the distance between the panel and the wall of the room, or 3 λ by 4, and so on—all its odd multiples like that. Then we will get better absorption here,



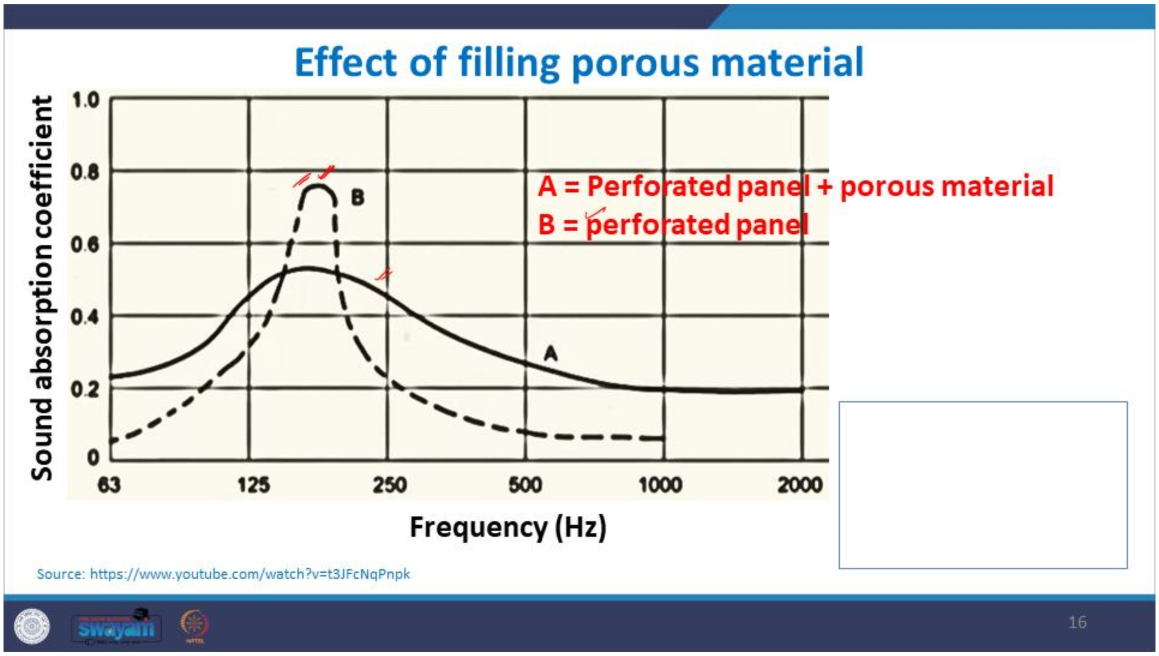
whereas if, suppose, we had the same— Same panel, everything is the same, just, you know, you are changing the air cavity depth. So, from the rigid wall, you are sort of keeping that panel here. And this distance is either λ by 2, λ, 3 λ by 2, and so on. Then, in that case, although you get the peak at the resonance frequency, it is very low in magnitude. So, this is not the optimum case, okay, whereas this is.




What is the effect of filling the porous material? So, you know, we have an open air cavity, just like, you know, in the case of perforated—so we already studied about sealed panel absorbers. In the sealed panel absorbers, we had a confined air cavity behind the panel and the rigid backing. If you fill that with a porous material, what happens? It improves the damping and broadens the peak, okay? So, because it leads to further absorption. So, the same kind of effect can be observed here. Basically, the porous material is acting as some kind of damping which is being added. So, the effect that is observed is that it slightly decreases the absorption value at the resonance peak, but it increases the absorption values in the other mid and high frequencies. So, overall, it leads to a broader absorption curve over a wider frequency range. So, if the porous filling is not there, we observe very sharp peaks. In all the resonance absorbers, such as the Helmholtz resonator, panel absorber, or the perforated panel absorber, they all have one particular limitation. The limitation is that their absorption peak is very sharp and focused around a targeted resonance frequency or a targeted fundamental frequency. But you can overcome this limitation by adding a porous filling.




So, here a porous filling has been added. So, what has happened? This sharp and narrow curve, which was initially present for a simple perforated panel, has now become more broadened, but this has come at the cost of a decrease in the magnitude of the absorption. So, this is the effect of adding porous material.




So, let us quickly see the advantages: you can achieve low-frequency noise control using this. You can tune the dimensions of the cavity depth and the radius. So, you already know the expression for the fundamental frequency, which is this one. So, you can accordingly tune sigma, t, and d—these three parameters you can adjust to get any fundamental frequency you would like, okay? So, within the constraints of manufacturing, if you are able to attain some sigma, t, and d, then you can definitely obtain some low value f as well, okay? So, ideally, if there is no limitation to manufacturing, then any kind of fundamental frequency can be obtained by tuning the sigma, t, and d of that panel. And hence, we can obtain a low value f as well, and low-frequency absorption is then possible, okay? Unlike the porous fibrous absorbers, it is very selective high-end noise control that can be used, and it is more durable than the porous fibrous absorbers because we have a stiff lamina—there are no loose fibers, etc.

## Advantages of Perforated panel absorbers

- **Low-frequency noise control** is possible (< 1000 Hz), unlike using just porous-fibrous absorbers.
- Can be used for **extremely selective high end noise control applications.**
- **Durable**

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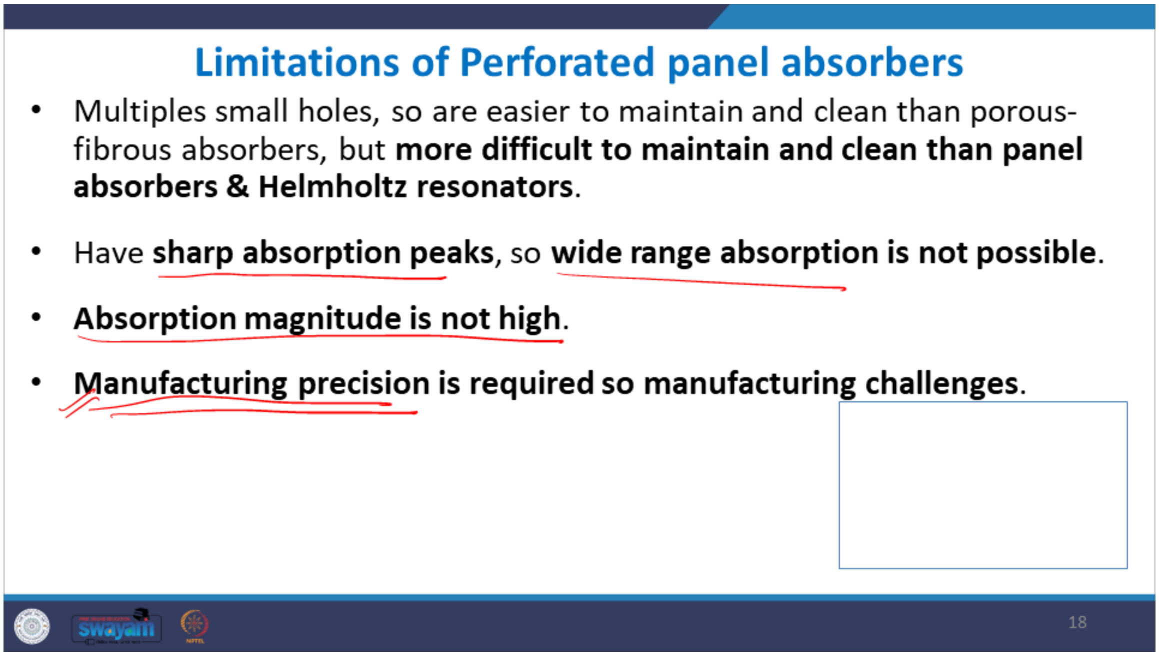
The limitation is that you have multiple small holes. And instead of compared to a panel absorber or a Helmholtz resonator, they are more difficult to maintain and clean because there are so many holes and perforations which again should be of the uniform size. So, there is first a challenge in manufacturing of these panels. because any inaccuracy in the manufacturing can tailor and change the absorption response. And at the same time, any kind of corrosion that happens, rusting that happens on the sheets or the clogging or just the settlement of some dust or soot particles over the panel can lead to a change in its absorption response because these holes can get clogged or changed. Okay, sharp absorption peaks are there very, you know, kind of common limitation. So, wide range absorption is still not possible. Magnitude of this absorption is also not high. We have seen here, it is a very low absorption magnitude. So, although it is higher than porous fibrous for some lower frequency range, it is still not high enough and then manufacturing precision is a major limitation which is there.




What is the common application of this perforated panel sound absorbers? They are commercially available as these sound box units. You can see, you know, if you go to a radio shop or a music system shop, you can see these kind of sound boxes. They are covered with a perforated panel sheets. And what are they doing here? They are usually, you know, tuned to target all the frequencies below 250 Hz. So, basically, improve the music quality. And reduce the effect of the low frequencies in the music. Okay. Usually, the material is made of plastic, wood, plywood, or metal, and the application is targeted low-noise control, especially in musical systems. Okay. When you have speakers or some kind of other music-synthesizing devices or music reproduction devices, you want to cut down bad noise, which is beyond 250 hertz, and you want to enhance your music quality.

## Applications of Perforated Panel Sound Absorbers

- Commercially available as "**Sound Box Units**"
- These are boxes with slotted cavities covered by perforated panels.
- They may have fibrous material fillings.
- They may have metallic septum to create breaks in between chambers.
- Target frequencies < 250 Hz.

Source: https://www.amazon.com/Alloet-Speaker-Stereo-Player-Decoder/dp/B07LF6FBZD

- Panel material: plastic, wood, plywood, metal.
- Application: targeted low noise control.



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

**Thank You**