NOISE CONTROL IN MECHANICAL SYSTEMS

Prof. Sneha Singh

Department of Mechanical and Industrial Engineering

IIT Roorkee

Week:03

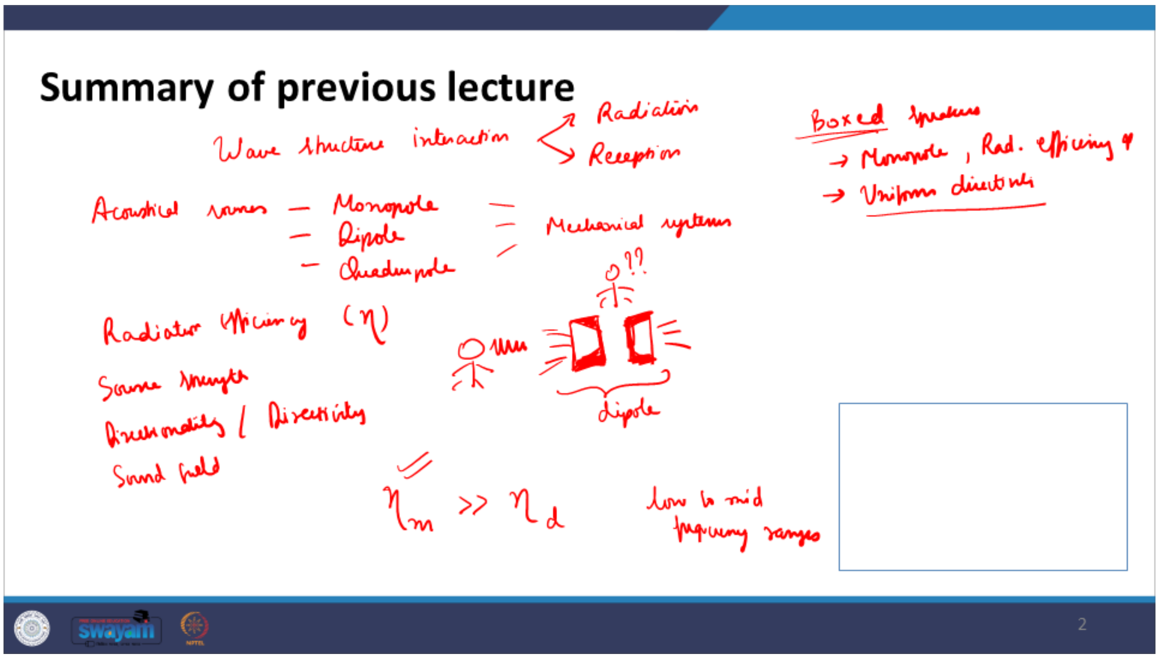
Lecture:11

Lecture 11: Radiation from Common Acoustical Sources – 2

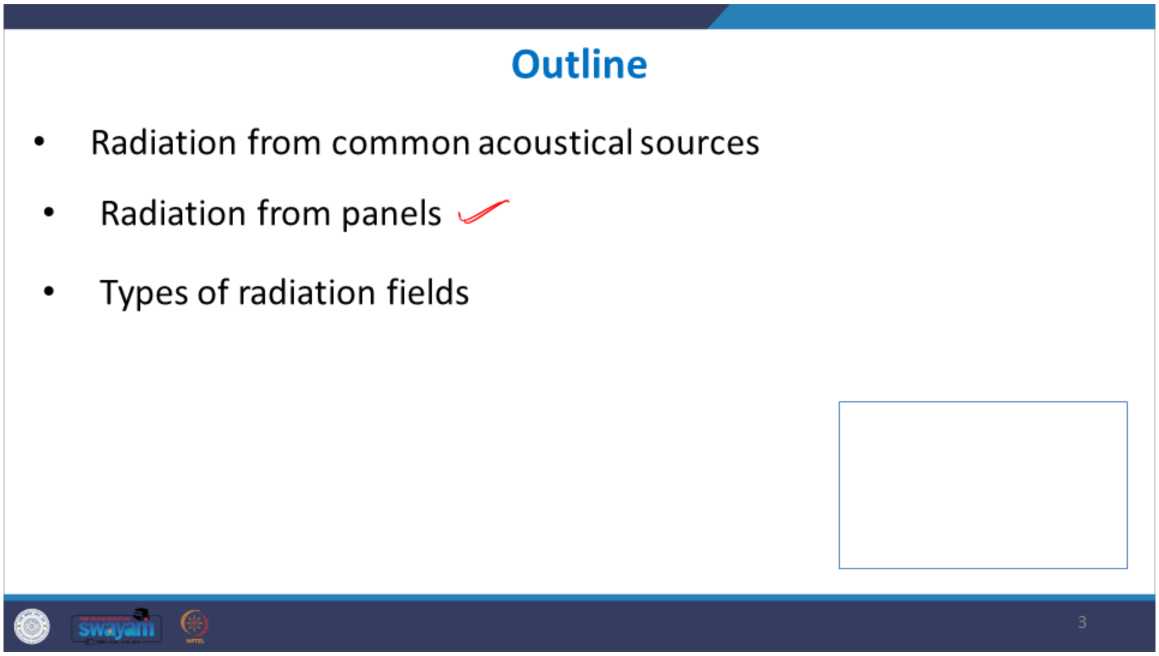
Welcome to Lecture 11 in the series on noise control in mechanical systems with Professor Sneha Singh. Myself, and this lecture is the continuation of the previous lecture, that is the radiation from the common acoustical sources. So, previously we studied about what do you mean by wave-structure interaction and wave-structure interaction. It is essentially when it is from structure to fluid we study radiation, and when it is from fluid to structure we study the reception. And then we studied about some simplified acoustical sources: monopole, dipole. Quadrupole, and they are common. These sources are found in various mechanical systems, what kind of machinery or mechanical systems generate these kinds of behaviors as if they are these kinds of sources, and generate an appropriate sound field based on the type of source it is behaving like.

Then we studied about the radiation efficiency. So, these concepts were introduced, which is denoted by the symbol eta because eta for efficiency, and then source strength, directionality or directivity of the different sources, and then sound field and how. You know, directivity or directionality is important because suppose you have a particular source, then you know what is the directivity pattern like. So, you know that at what zones the pressure would suddenly be low. So, one simple exercise: suppose you have got two unboxed speakers and you place them one behind the other. Okay, so suppose you have got one unboxed speaker like this and the other unboxed speaker like this, placed opposite to each other. They behave like an acoustic dipole because these are like two monopoles. So, suppose these boxed speakers, these are boxed speakers. Each of them, because in the market usually you find the boxed speakers. So, they behave like a monopole and they radiate. So, when you stand here you hear a lot of noise, but when you stand here you hear no noise at all. So, you can do these experiments at home and see for yourself how it behaves, and how, in certain regions, the sound pressure could be quite high, whereas in certain regions, it could be nullified, and you hear very low sound pressure or very low noise. Another kind of inference we can draw is, if you see in the market, you get such boxed speakers. Why do you get the speakers boxed inside the cabinets? Why are they popular? Because we studied in the previous lecture that the radiation efficiency of a monopole is much greater than the radiation efficiency of a dipole under reasonable frequency ranges, low to mid-frequency ranges, where most of the sound sources are Common sound sources are. Therefore, suppose we had a speaker, and we want the speaker, which is usually used for playing sounds, music, various kinds of music, etc., and we want to amplify it Then, how to do it very efficiently, especially in concerts, etc.? We can have multiple such speakers, and we want to amplify the sound. We can do it through electronic amplifiers, but at the same time, if you place the same speaker against a rigid backing, either place it against a rigid wall or box it in a rigid wall Oh, sorry, or you sort of enclose it in a rigid box. Suddenly, it becomes a monopole, and the sound pressure or the sound emitting from the speaker amplifies in magnitude. So, that's why box speakers have become very popular because they are able to amplify the sounds, and also, not just that, because they are able to amplify the sounds, but at the same time, because now they behave like a monopole, they have a uniform radiation pattern. That's why box speakers are more popular than unboxed speakers because they behave like monopoles.

Radiation efficiency is much higher, and at the same time, they have uniform directivity because that is what you want. You do not want to place a speaker in a room where some people can hear the sound, some people hear it low, and some people hear it high. We want uniform directivity and a uniform distribution of the sound pressure. So, we sort of facilitate that it behaves like a monopole instead of a dipole.



Okay, so in this one, we will again see and continue our radiation from common acoustical sources, and then we will find out the radiation from the panels. It is an extended real-life source and then the various types of radiation fields.



So, continuing from the previous lecture where we were finding the efficiency of a dipole with respect to a monopole, let us now do that exercise for the quadrupole. So, the sound power of the quadrupole is given by this equation.

$$W_{LAT} = \frac{\rho_o c k^6 (Q L_1 L_2)^2}{480\pi}$$

So, let us find what the radiation efficiency of this lateral quadrupole is with respect to a monopole. So, this should be

$$W_{LAT} = \frac{\rho_o c k^6 (Q L_1 L_2)^2}{480\pi}$$

and the W_m, as found in the last class,

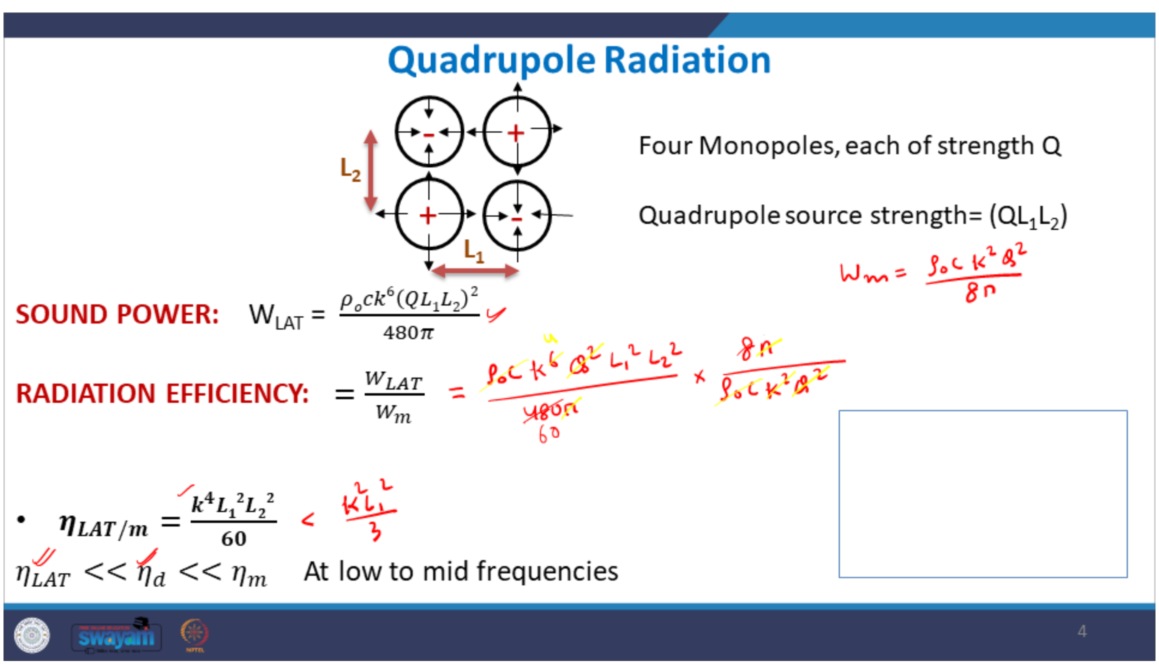
$$W_m = \frac{\rho_o c k^2 Q^2}{8\pi}$$

Then this becomes π. If you solve it, let us see what we result with. So, ultimately, you would end up

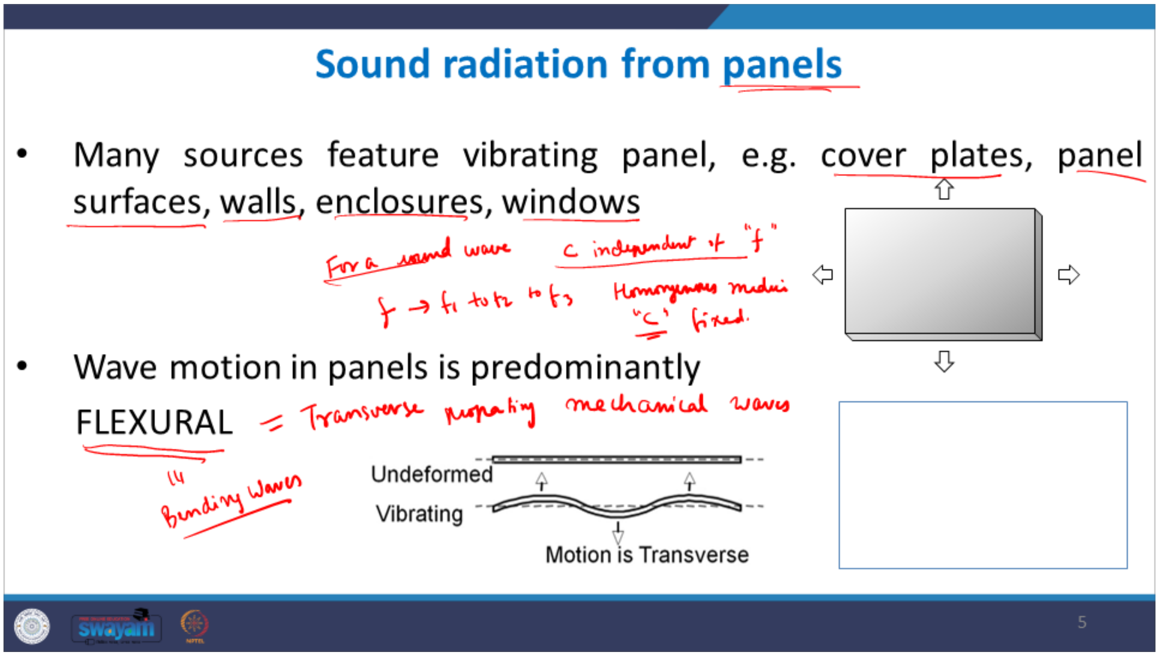
$$\eta_{LAT/m} = \frac{k^4 {L_1}^2 {L_2}^2}{60}$$

So, as you see here, for small low to mid-frequency ranges, this term is even smaller than this term here that we had found for the previous case.

So, which means that the radiation efficiency of a lateral quadrupole is much lower than the radiation efficiency of the dipole, which again is much lower than a monopole. So, from the noise control point of view, if, by some means, we are able to convert a monopole source into a dipole and even better, if a monopole source can be converted into a lateral sort of quadrupole, then the radiation efficiency is going to go down heavily, and we are able to attenuate the sound waves that that particular source is generating. So, suppose we have a monopole source. By some way, we can have another source coming up which becomes anti-phase with it; then suddenly, we can bring down the noise source. So, that's one of the inferences we draw and something which is a takeaway for the noise control engineers.



Now, let's see the radiation from a real-life source, which are these panels—so large vibrating panels. You can find them in a lot of mechanical structures, such as the cover plates. Various kinds of machinery panels, walls, enclosures, windows; you have so many panels, you just look around and you find so many. Sources or so many objects that are in the form of flat panels, large panels. Okay, so it is one of the very common sources of sound radiation, and the reason we are studying it is that it has a peculiar phenomenon. Till now, most of the sources that we said or the simplified source models were vibrating, and they were creating the sound waves. And in the sound wave, what is the case for a sound wave? Whenever it is created and propagating in the medium, the speed is independent of the frequency of that wave. Okay. So, if the frequency is changing from f_1 to f_2 to f_3, but if the medium is continuous and homogeneous, it will be a fixed c. okay. The speed is independent of what frequency of wave you are creating. But when you know the panels, they vibrate, and the waves pass through them, usually they are predominantly flexural in nature. Now, what do you mean by a flexural wave? It is different from a sound wave because sound waves are longitudinal in nature. These flexural waves are transverse propagating mechanical waves. The definition of longitudinal and transverse waves has been given in the very first lecture. So, if you see what happens here, here the plate vibrates or the particles of the plate or the mass that is vibrating in the vertical to the plane of the plate. So, although the wave is propagating forward or downward along the plane, the particles are vibrating perpendicular to the plate. So, in 1D, you can think that if you have a tight string or a tight rope, and you strike it or pluck it, you will see these transverse waves where the disturbance propagates along the length, but the vibration is perpendicular to the length. So, the same thing applies if you now expand it to 2D; you understand the concept of these flexural waves. We also call these flexural waves bending waves.



So, what is the bending wave speed? We represent it as c_b here in this lecture. So, here is the overall equation for bending wave speed. As you can see here, this

$$c_b = \left(\frac{\omega^2 B}{\rho_s}\right)^{1/4}$$

$$\omega = 2\pi f$$

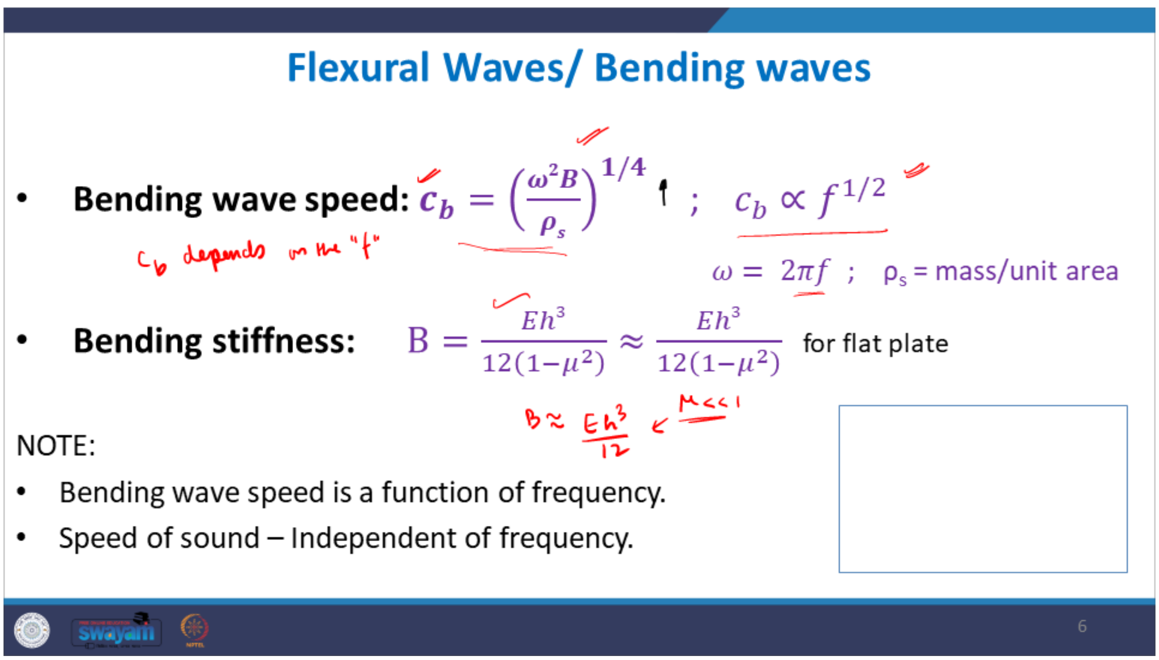
So, the bending wave speed is directly proportional to the square root of the frequency. So, here in the bending wave, the c_b depends on the frequency, unlike in a sound wave. Okay. Whereas, in the sound wave, it was independent of the frequency. So, here we have this term B; B is the bending stiffness for a flat plate. This is the equation of the bending stiffness.

$$B = \frac{Eh^3}{12(1-\mu^2)}$$

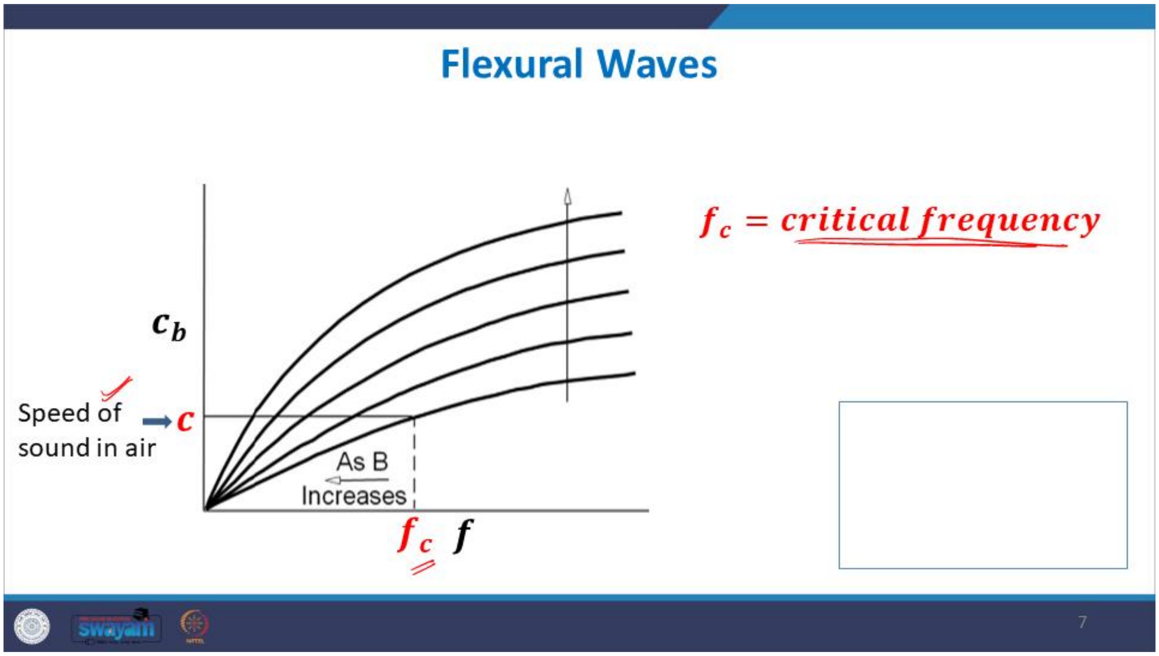
Okay. So, just a small correction here: suppose μ is very small, then this B would be approximately

$$\frac{Eh^3}{12(1-\mu^2)}$$

When the μ is very, very small. Otherwise, this is the full equation for the bending stiffness of the plate, and ρ_s is what? It is the mass per unit area of that plate, okay. Now, let us see here. This is a typical graph. You know that c_b is proportional to the square root of the frequency.



This is one of the graphs where we are plotting cb with respect to frequency f, and this is the square root dependence. As you know, as f increases, c_b also increases, but not directly proportional; it is not increasing as much as the increase in f. So, just imagine, you know, we are increasing the frequency, and you are observing that cb increases, okay, following this relationship. So, there would be a point in time when, at a certain frequency, c_b, which is the bending wave speed in a flat plate, should become equal to the speed of sound in the surrounding medium, which in most cases is air. So, when c_b becomes equal to the speed of sound in the surrounding medium, then that particular frequency we call the critical frequency.

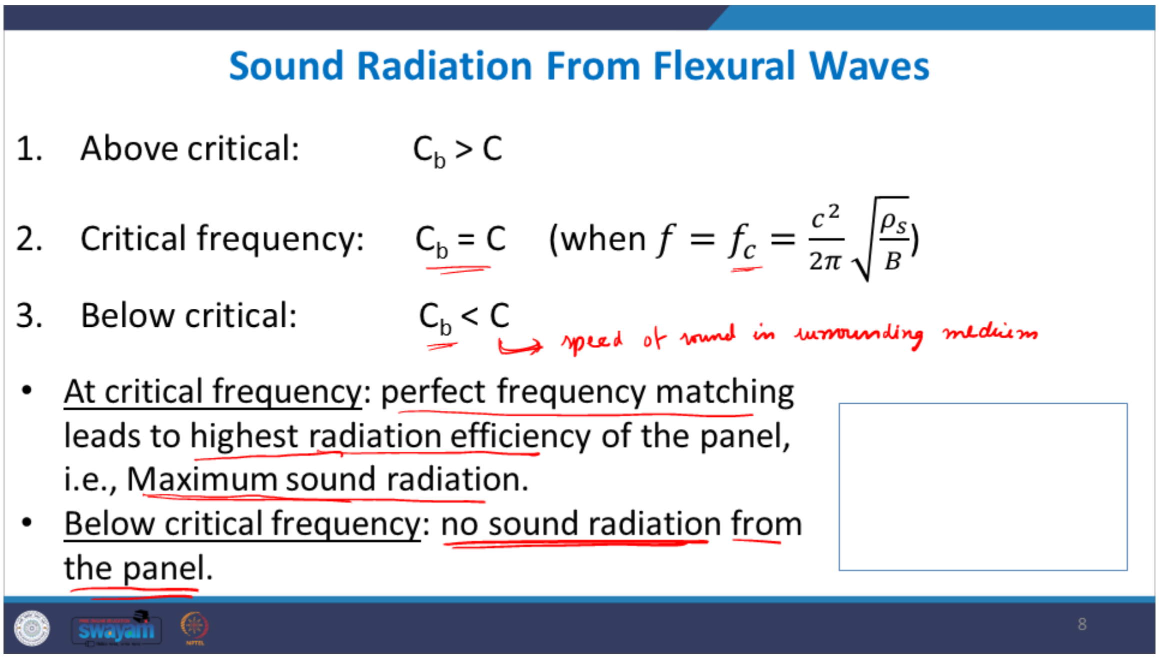


Now, there are three different types of zones of consideration: one is below the critical frequency. So, until the time the bending wave speed is smaller than the speed of sound in the surrounding medium. Okay. So, in most cases, it is air, but it could be water also. So, if you have a kind of plate in water or any other medium, the same will hold true. So, this is what?

This is the speed of sound in the surrounding medium, okay. So, till the When the bending wave speed is below the critical frequency, there is no sound radiation that happens from these plates or panels, okay. Then comes the region where you have a critical frequency when c_b becomes equal to c, and when you equate it in this equation over here. So, you put this c_b as c and you find out the corresponding f_c that is creating this c. So, from this equation, if you solve, you will ultimately get that this critical frequency is

$$\mathbf{f = f_c = \frac{c^2}{2\pi}\sqrt{\frac{\rho_s}{B}}}$$

So, at that moment when these are becoming equal, you will have maximum sound radiation. Okay. There is a perfect matching that is happening, and the radiation efficiency is actually the highest.



Then above that, above the critical frequency, Okay, the sound radiation happens but at a lower rate. So, what we see here is that below the critical frequency, the same plate is not able to generate sound waves even though it is vibrating. It is having a bending wave, but it doesn't act as an acoustical source and it doesn't radiate away sound waves. At the critical frequency, suddenly there is a very high radiation, and then below that, that radiation goes down but it is there, okay. So, this radiation, so here let's say this was the plane of the plate which is along the xz plane, and then the sort of plate sort of has some flexural wave that is set in the plate in the xz direction. So, we are showing a 2D view here, so this is a transverse wave.

So, the direction of the propagating wave is along this xz plane, along the x-axis here. The wave is propagating like this. How do you find out the relevant direction of the sound waves it is creating above the critical frequency? So, if you draw the lines, you know, parallel to this waveform at the trough. So, from the trough, you draw these tangential lines.

From the two successive troughs and then a perpendicular line from this. So, that gives you the direction of this particular thing, which is the direction of the sound waves it is creating. Here, the distance between these two troughs becomes the λ_p, or rather, I should call this λ_B because it is a bending wave. Okay, and this is what the λ of the sound wave it is generating is. You can see that the λ of the sound wave is smaller, so what you see here is that the λ of the sound wave is smaller, but the frequency obviously is the same. Let's see an interpretation of this λ, which is given by

$$\lambda = \frac{c}{f}$$

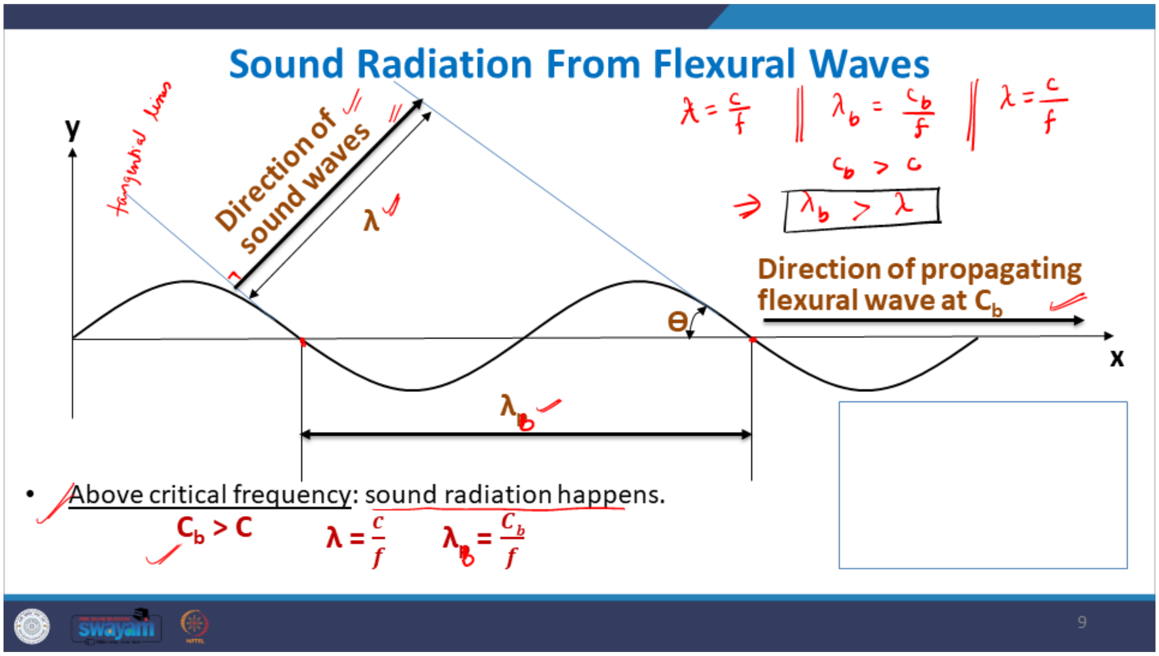
For the bending wave,

$$\lambda_p = \frac{Cb}{f}$$

and for the sound wave it is creating, this

$$\lambda = \frac{c}{f}$$

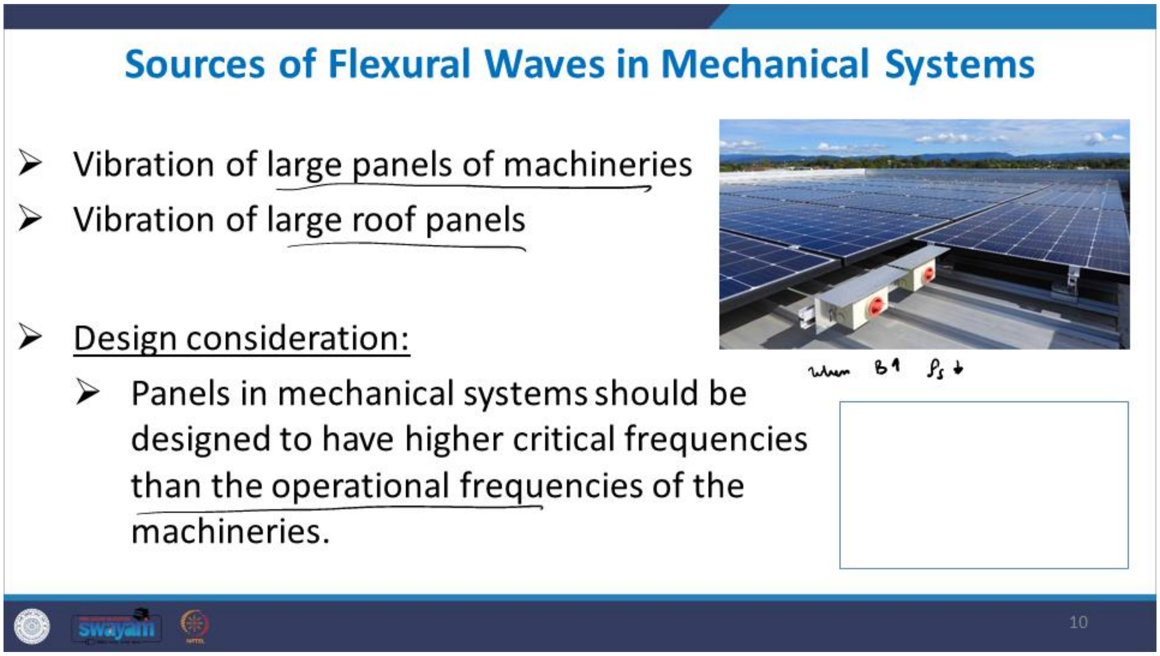
The f is the same, but C_b is greater than C. So, λ_B is greater than λ, as you can see here graphically. Okay, that happens above the critical frequency.



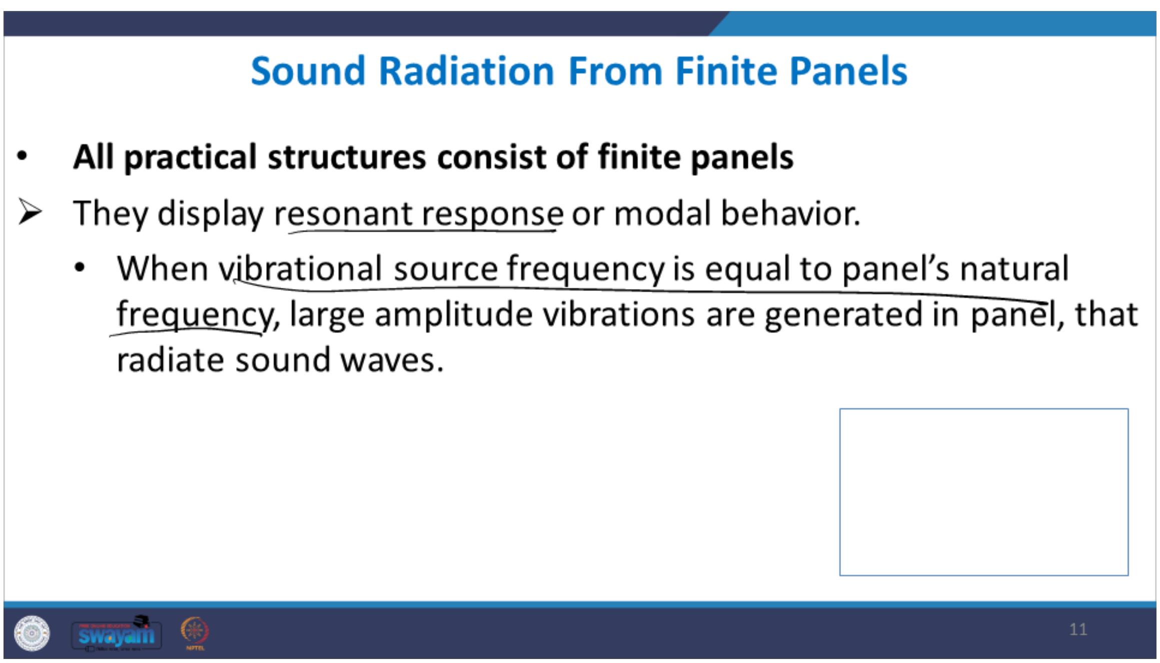
Now, some of the sources of flexural waves in mechanical systems, now let us get and see what happens in the mechanical systems. You have large roof panels, you know, and then various machineries have large panels, large roof panels, and any kind of panel or flat plate surface would be acting as a source of flexural waves and would be able to radiate the sounds above the critical frequency, not below it. So, what could be a design consideration with respect to, if suppose a noise control engineer looks at this particular phenomenon? So, what is the inference or a takeaway for a noise control engineer? So, the design consideration for a noise control engineer is that you have to design the panels in such a way that they have a high critical frequency.

So, this value here has to be high. How can it be high? When you increase the bending stiffness or you reduce the mass per unit area. So, basically, you can make it have a high critical frequency when you either increase the bending stiffness or you reduce the mass per unit area. In that case, their critical speed is very high, and hence at a higher frequency, there is a matching.

So, because below the critical frequency, we do not have radiation. So, the higher the critical frequency, the higher the operational frequencies of these machineries. So, if the critical frequency is higher than the operational frequency, then it would not be able to radiate. So, that is the aim.



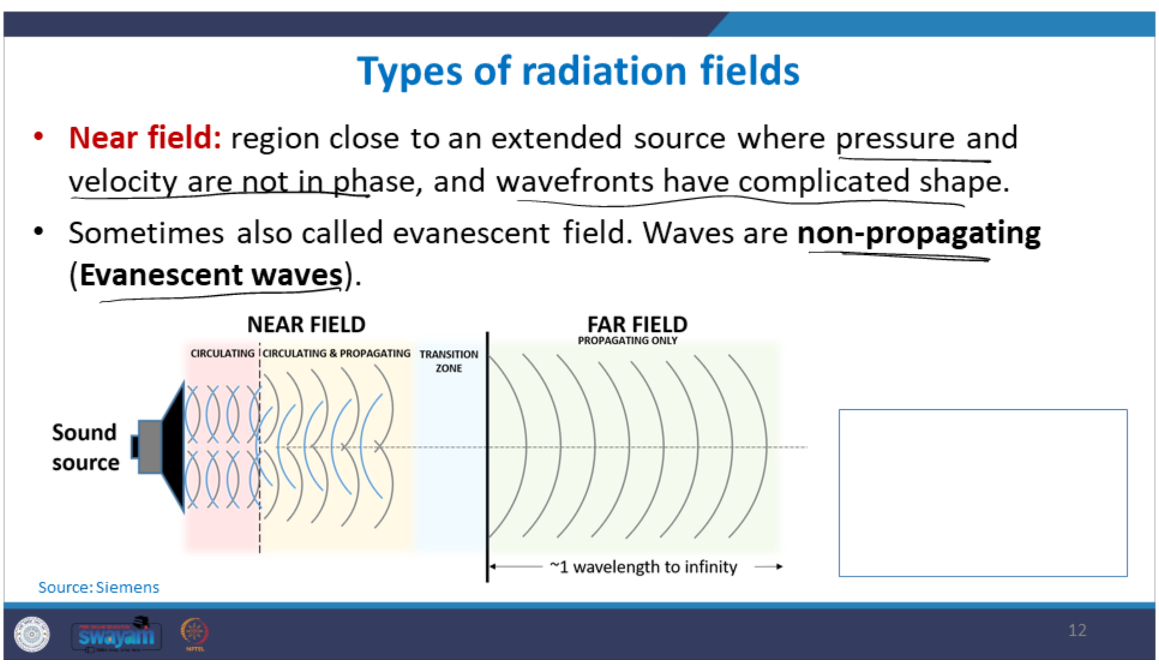
And from the finite panels, there is a resonant response, which means that they are able to have a large amplitude of vibrations when the natural frequency matches with the vibrational source frequency.



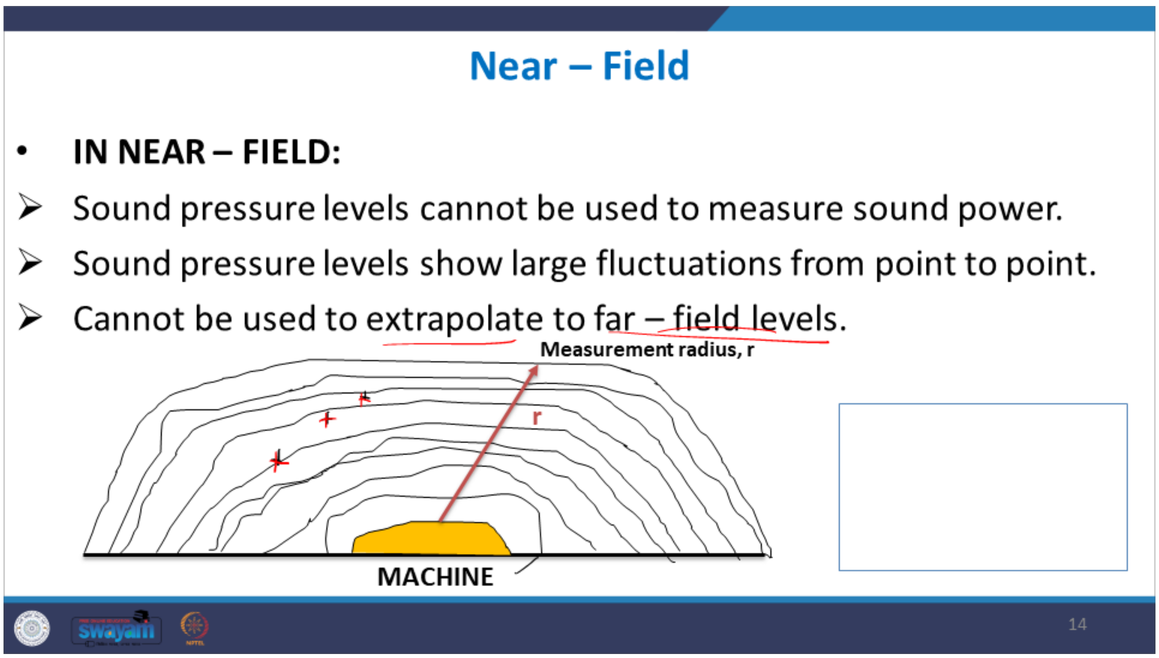
Now, types of radiation fields. So, so far we saw that different sources have different fields: a monopole has a spherical wave front and a spherical wave front distribution, a dipole has a dumbbell-shaped distribution, and so on. But all of those distributions that we obtained were under the condition that the radiation is obtained in a far field with free field propagation; they were not representing the near field effect. So, how the source behaves and how the sound waves propagate are only valid within a certain extent in the spatial dimensions. So, there are different fields associated with it, and so far, all the fields that we studied in the previous lecture and all the equations we dealt with in the previous lecture were free field propagations.

So, what do you mean by a near field? Suppose you have a source. So, very near to the source, the pressure and the velocity are not in phase. The wavelength has very complicated shapes, okay. They are non-propagating waves, also called evanescent waves, okay.

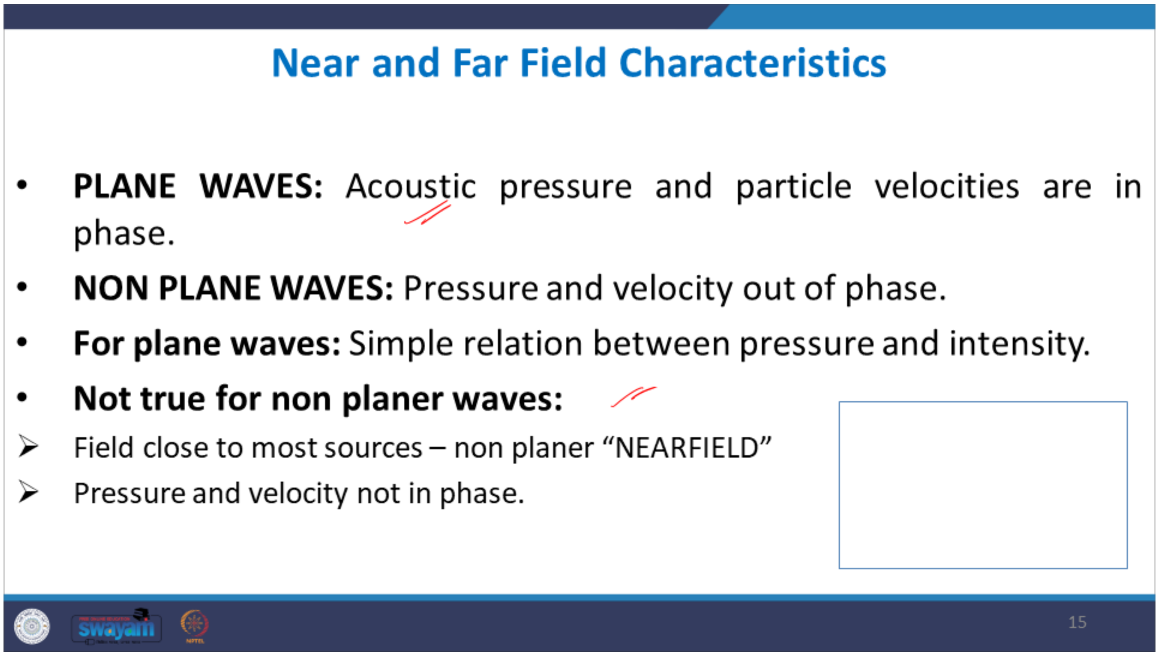
And then, as you move a bit away, you finally reach the far field region where the acoustic pressure and particle velocity come in phase, and the wave becomes propagating in nature, and you get the far field. So, this is so whatever radiation field we studied or the equations we derived, it was for this region, not for the near field. In fact, the near field is where you should not be making any measurements or doing any kind of acoustic manipulation because they do not truly represent a sound source.



Suppose you have a machinery source; the near field sound source could have a very complicated kind of shape. So, if you made the measurement of the machinery in some places here, okay, in some places here, it would not truly represent how the source behaves at a large scale, okay? So, you cannot extrapolate whatever you find to the regions beyond a certain level, beyond a certain extent. So, in general, the practice is that whenever we try to measure the noise of any machinery, we keep a certain distance. It's not like we have a machinery and we directly place a microphone just next to it. It's not going to give us the true representation of the field from that machine resource, okay?

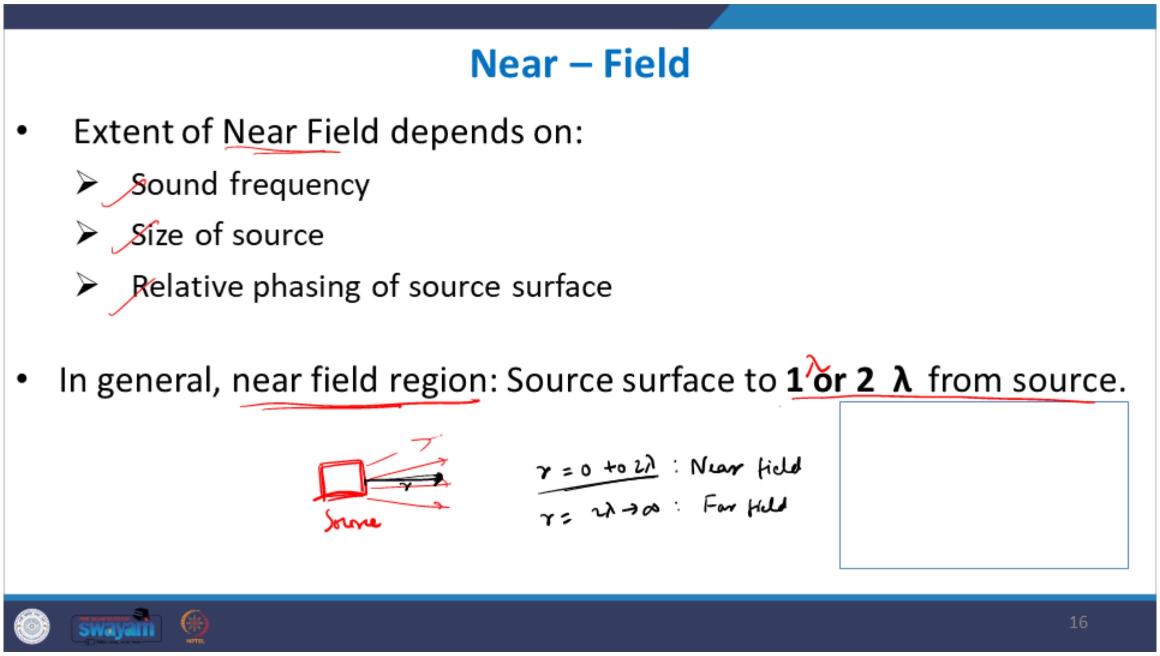


So, we have to move to the far field where finally they become in phase and propagating in nature.

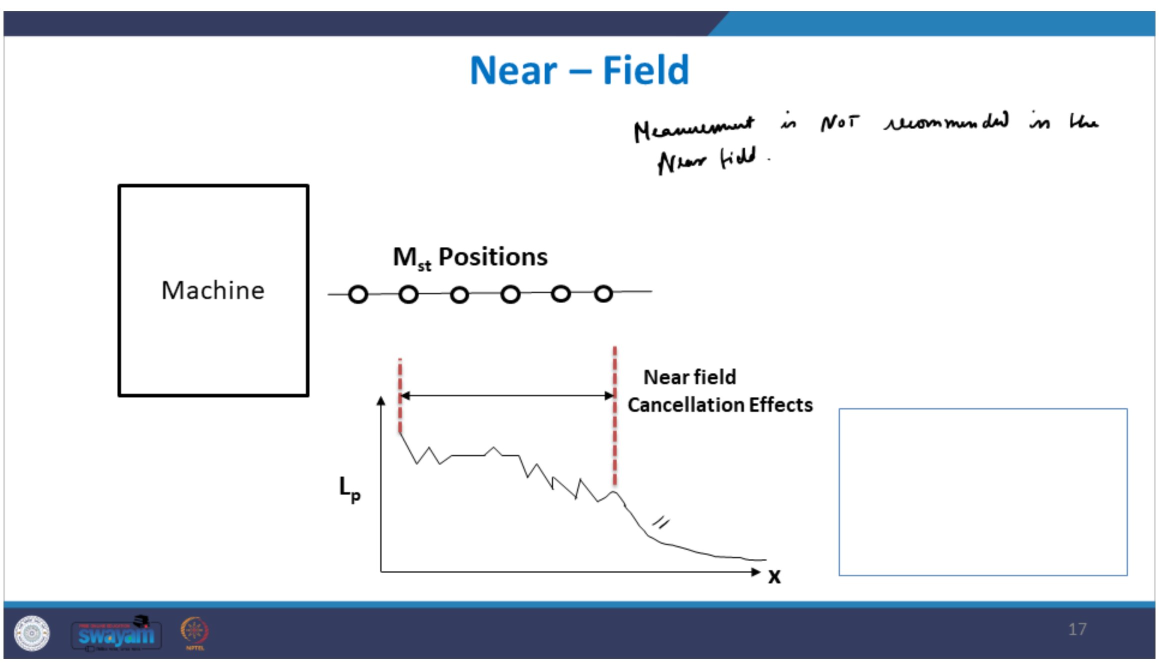


So, what happens, you know. So, how do you determine what is the extent and what is the extent beyond which we have to make the measurements to get a true representation of the source? So, the near field depends on the source frequency, the size of the source, the phasing, and in general, the near field region for a source is between somewhere between the surface of the source to up to 1 to 2 λ from the source.

So, 1 λ to 2 λ from the source. So, let us say if this is some source, okay, which is sort of creating these sound waves, then the near field region is, and this is the distance r from the surface of the source, then the near field region starts from r is equal to 0 till around 2 lambda, to be on the safer side, beyond which we have the far field region, 2 lambda till almost infinity. In case of an open case, we have the far field region, okay.



So, we do not make, you know, measurements in the near field, okay? Measurement is not recommended in the near field, as already stated. It is not a true representation of the source. There are a lot of near field cancellations that happen, and it is only after that that it starts behaving like what we have studied. So, that is the thing.

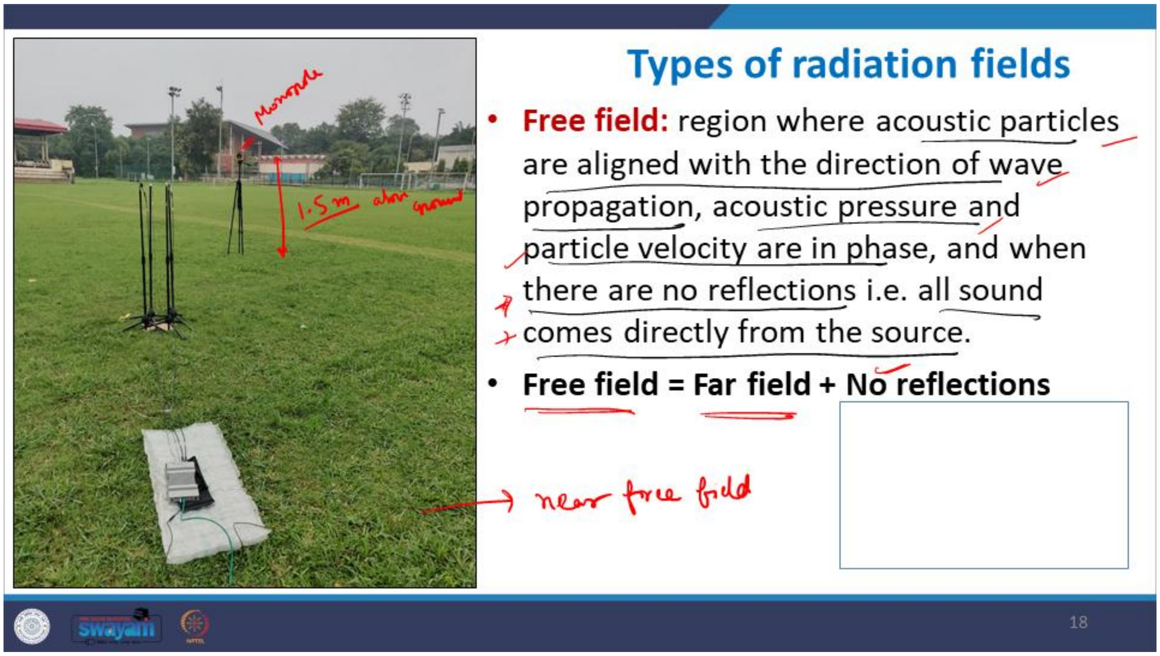


Now, let us see some of the types of radiation fields. We have seen the near field and the far field so far. We also have another radiation field called the free field. What is the free field?

It is a region where the particles are aligned with the direction of the wave propagation. The pressure and the velocity are in phase, and in addition to that, there are no reflections. All the sound that is reaching a point is directly coming from the source. So, if you see here, this is what happens in the far field: all of the above conditions, and these conditions are what happens when there are no obstructions or changes in media. So, the media remains infinite and homogeneous without any change in media occurring.

So, the free field can essentially be a far field plus the no-reflection condition. This particular photograph, you know. So, obviously, in real life, a perfect free field is almost impossible to achieve, okay? We cannot achieve a perfect free field, but we can try and come close to a near-free field. So, this again is a photograph from one of the research studies we did for sound source localization.

It has been published in various journals, which you can Google and read for yourself. So, what happened here is that we have an open football stadium where the nearest obstructing surface is far, far away. Many λ away from the source, and we have a box speaker; it is acting like a monopole. Okay, and it is almost 1.5 meters above the ground to avoid reflections from the ground, and all the reflectors or any kind of change in the media or any kind of new medium or surface or structure is quite far away from the source. So, here it is acting like a near-free field where you know you are getting a propagating wave.



So, what is happening in the free field? All the equations we derived, you know, the equations for sound wave propagation, the equations for sound wave propagation in the medium boundaries, all of that, you know, they are true in the free field. So, in the free field, spherical waves follow this kind of attenuation rate:

$$\mathbf{p_{rms}} \propto \frac{\mathbf{1}}{\mathbf{r}}$$

Okay. and in the cylindrical waves,

$$\mathbf{p_{rms}} \propto \frac{\mathbf{1}}{\sqrt{\mathbf{r}}}$$

Now, I would like to state here that in the previous lecture, I think somewhere I mentioned P is inversely proportional to r squared. So, just rectify that it is inversely proportional to r. It is the intensity which is inversely proportional to r squared.

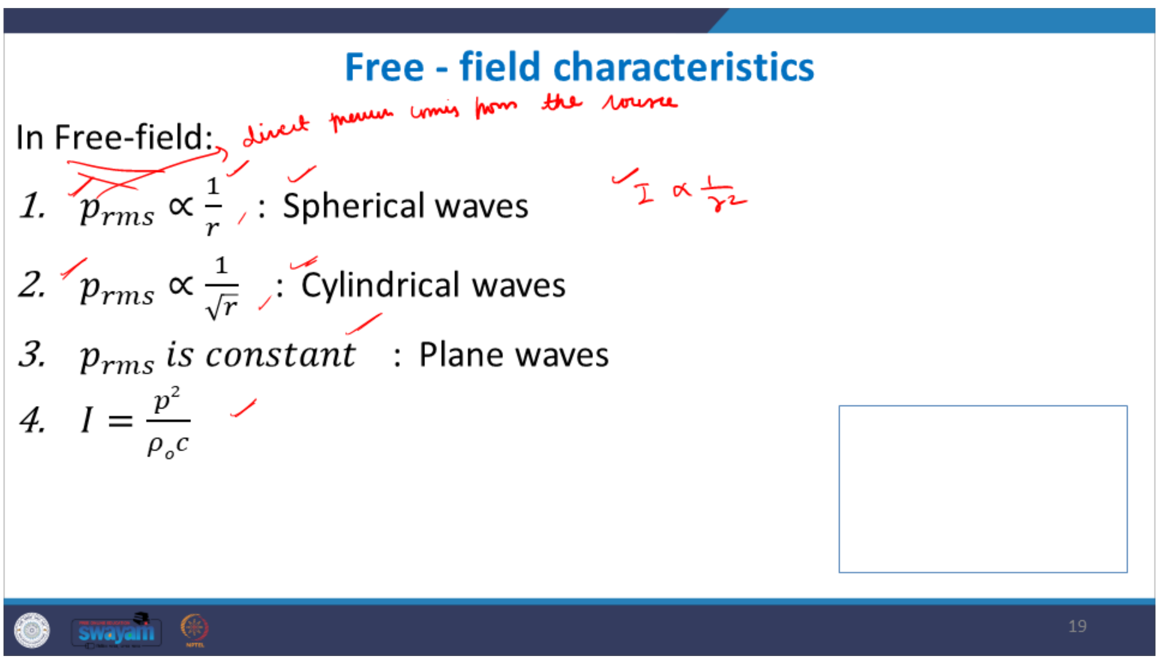
The pressure is always inversely proportional to r. So, just rectify that in the previous lecture. Then, this is what happens in the cylindrical waves, whereas for the plane waves, it remains constant.

$$\mathbf{p_{rms}\ is\ constant}$$

Then, this equation that we had derived for the intensity, which is

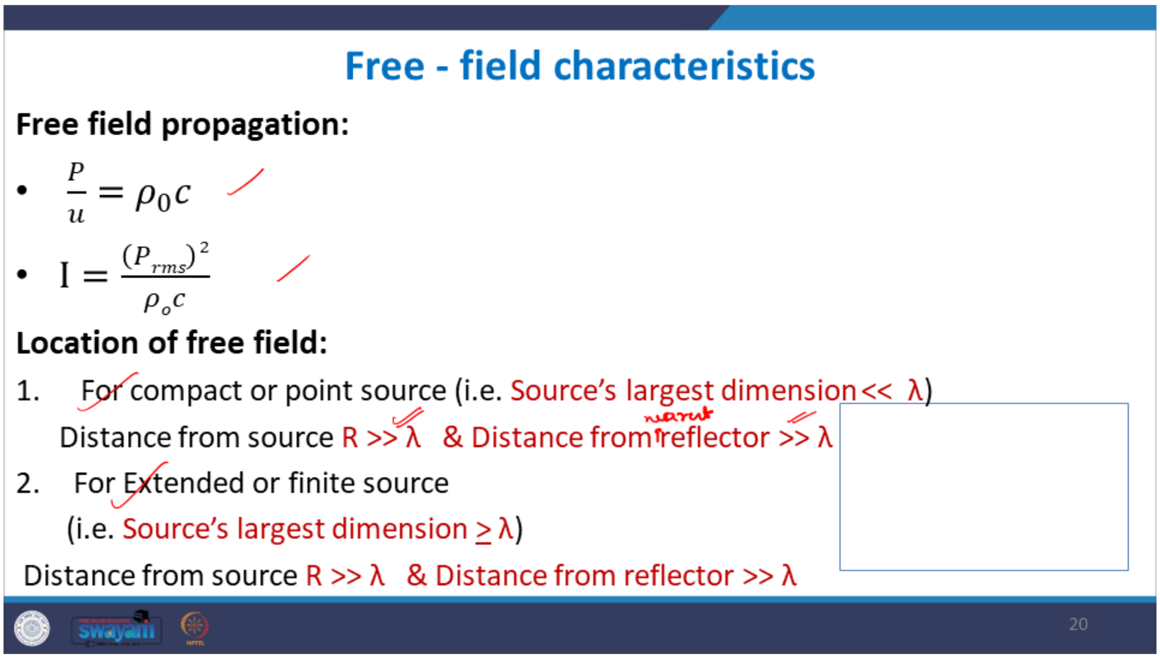
$$\mathbf{I = \frac{p2}{\rho oc}}$$

$$\mathbf{\frac{P}{u} = \rho_0 c}$$



All of these equations are valid for free field propagation. What is the location of the free field? So, here obviously you have to be in the far field and away from the reflector.

So, both conditions have to be satisfied. So, for both compact sources and extended sources, we have the same condition or location for a free field. The distance from the source should be much greater than the λ_{under} consideration, and the distance from the reflector also has to be much greater than the λ. So, any nearest reflector. You can say the distance from the nearest reflector.

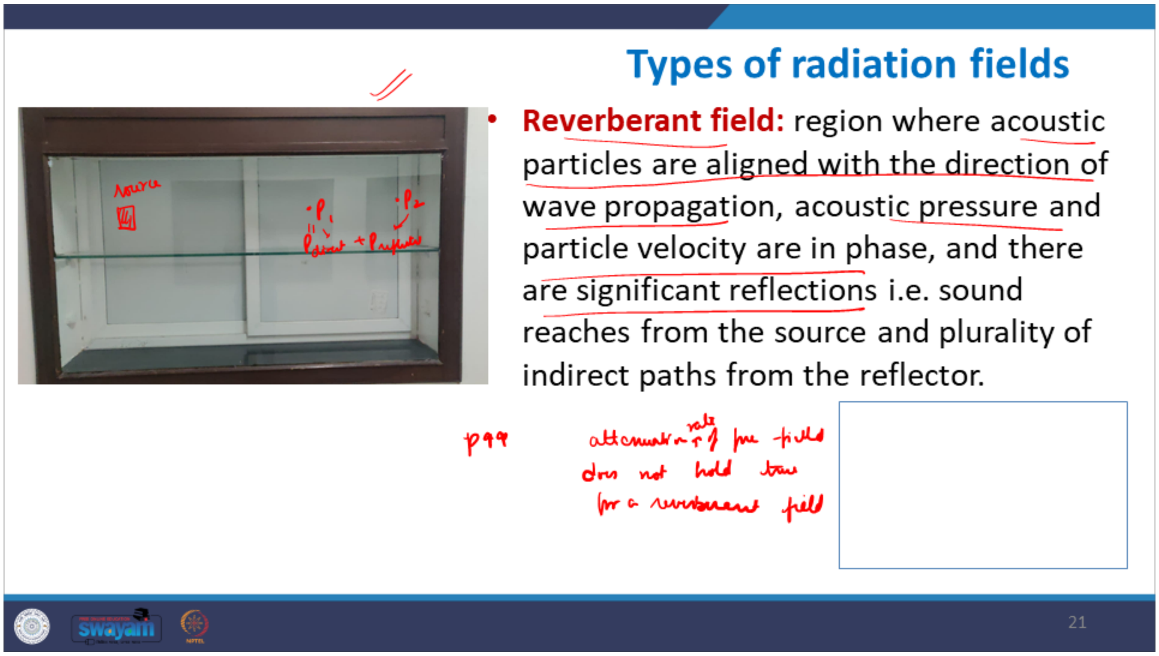


Okay. So, the last type of radiation field that we will deal with is the reverberant field. This is a snapshot of one of the boxed cabinets in our department that I took today, and I wanted to paste it and show you a reverberant field. So, what's happening here? This is a large cabinet that is surrounded on all sides with hard reflecting walls and then covered by glass on the other end. So, here you have a glass covering, and all the back walls are hard walls. Here, you have a small enclosed space.

With a lot of hard walls that are able to reflect the sound source. So, what happens here is that in the reverberant field, the region where acoustic particles are aligned with the direction of wave propagation, the pressure and velocity are in phase, but there are significant reflections as well. Okay. So, here at any point P, suppose we had a source in this field. And we measured it at any point P_1 or P_2, what we would get is that here the sound would be both P from the direct field plus P due to the reflected field in both these cases. Which means that the sound is arriving directly from the source, but also that same sound is reaching these reflecting walls and getting reflected, reaching the listener from multiple pathways.

So, essentially, what does a reverberant field do? It amplifies the pressure compared to what you would observe in a free field, okay? And the attenuation rate that is expected in the free field does not hold true for a reverberant field. If you have a perfect reverberant field, typically you experience a uniform distribution in the acoustic pressure, irrespective of the fact that if it is a spherical wave, it should attenuate at the rate of, you know, inversely proportional to r, or cylindrical, then inversely proportional to the square root of r, that is for a free field. The reverberant field shows almost uniform distribution if it is a perfect reverberant field, and the pressure amplifies because it is both the direct pressure. So, all of this was what? The direct pressure coming from the source.

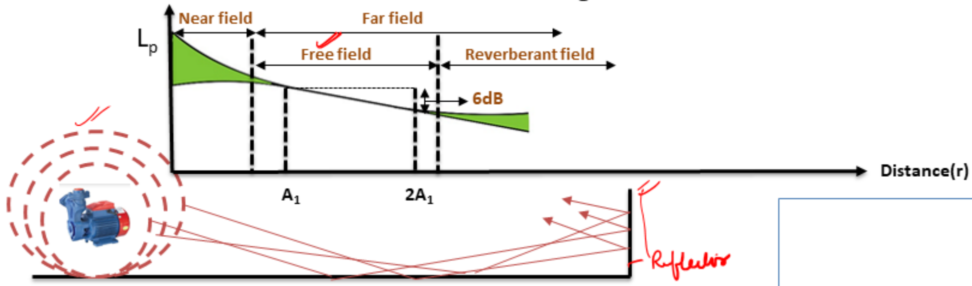
So, the direct pressure plus the indirect pressure coming from the deflected pathway. So, overall, the acoustic pressure amplifies, and that is why you observe that. Suppose you are moving around in, let us say, I will again come back to that. A football stadium, a very large football stadium, or a very large open field, and when the players are playing and they are shouting at each other, still the noise level is down. When they have to communicate with each other, they shout at each other because they are in a free field environment. But when the same players come into a closed room environment, the same person who was talking in an open field now suddenly starts talking in a closed room environment, the pressure level actually feels very high because it's a reverberant environment. And that is why, even in parties, you experience that. Suppose you have some DJ or some speakers that are in an open environment in the parties, then It does not bother you much, but you put the same DJ and the same speaker system within a closed reflective room in a party, and you will not be able to hear a thing. You will not be able to communicate properly because the sound level will amplify because now we have reached a reverberant environment.



Now, typically in practice, you know, you don't ideally get a perfect version of any such field. Suppose this is a machine resource, this is where it is placed, the nearest reflector is here; this is the nearest reflector. Then, you know, it starts from the near field; then you have the far field. Within the far field, for a certain region, you have the free field propagation, but then near these walls, you will have the reverberant field. And it is always recommended to make the measurement in the free field because there you expect, and you can get a sense of, the type of wavefront.

Sound Fields

In practice, the majority of sound measurements are made in rooms that are neither anechoic nor reverberant– but somewhere in between. This makes it difficult to find the correct locations where the noise emission from a given source must be measured.



A normal practice to divide the area around a noise source e.g. a machine into four different fields:

Near field, Far field, Free field, Reverberant field.

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

THANK YOU