NOISE CONTROL IN MECHANICAL SYSTEMS

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Week:2

Lecture:10

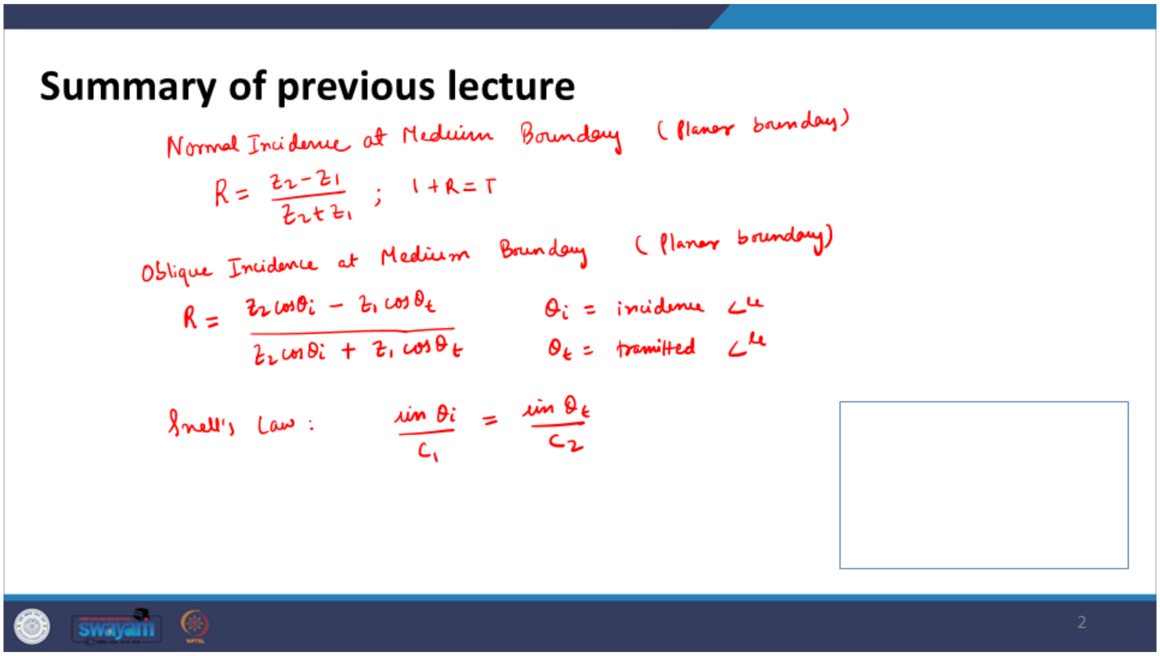
Lecture 10: Radiation From Common Acoustical Sources - 1

Hello and welcome to Lecture 10 in the series on noise control in mechanical systems. In this lecture, we start a new topic in acoustic fundamentals. This is a topic on radiation from common acoustical sources. I am Professor Sneha Singh from the Department of Mechanical and Industrial Engineering, IIT Roorkee. So, before we begin the radiation from common acoustical sources, let us summarize what we dealt with in the last couple of lectures. We were studying about the sound wave propagation from various boundaries, as in when there is a change in the acoustic medium.

The cases we discussed were for a planar boundary where the harmonic plane waves are being incident either obliquely or perpendicularly, and for the normal incidence case, we had the reflection coefficient as,

$$R = \frac{z_2 - z_1}{z_2 + z_1}$$

and this relationship between the

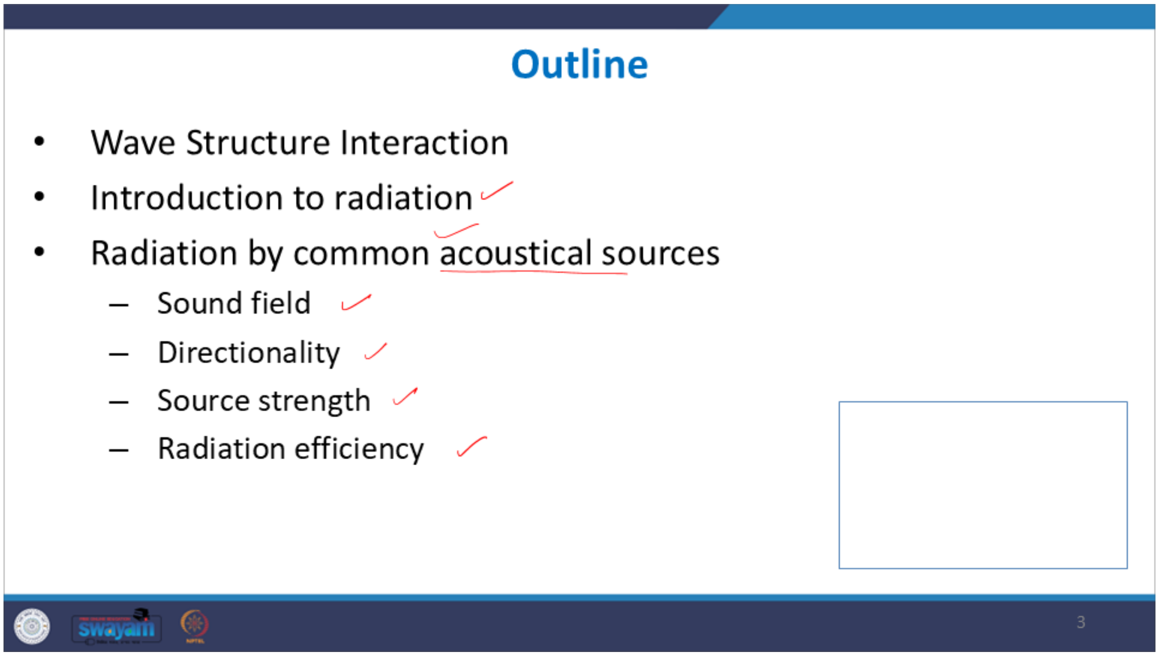


reflection coefficient and the transmission coefficient then for oblique incidence at medium boundary. Again, this is a planar boundary; this is also the case of a planar boundary. We had the reflection coefficient that was

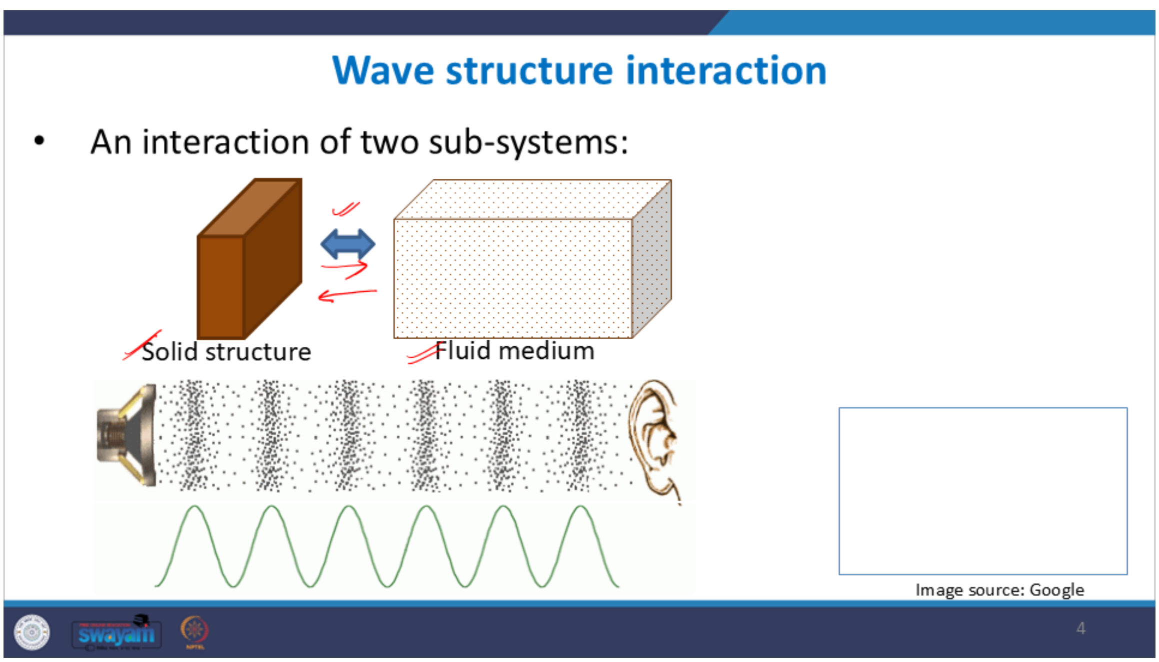
$$R = \frac{z_2 \, cos \, \theta_i - z_1 \, cos \, \theta_t}{z_2 \, cos \, \theta_i + z_1 \, cos \, \theta_t}$$

where θi and θt are the incidence angle and θt is the transmitted angle.

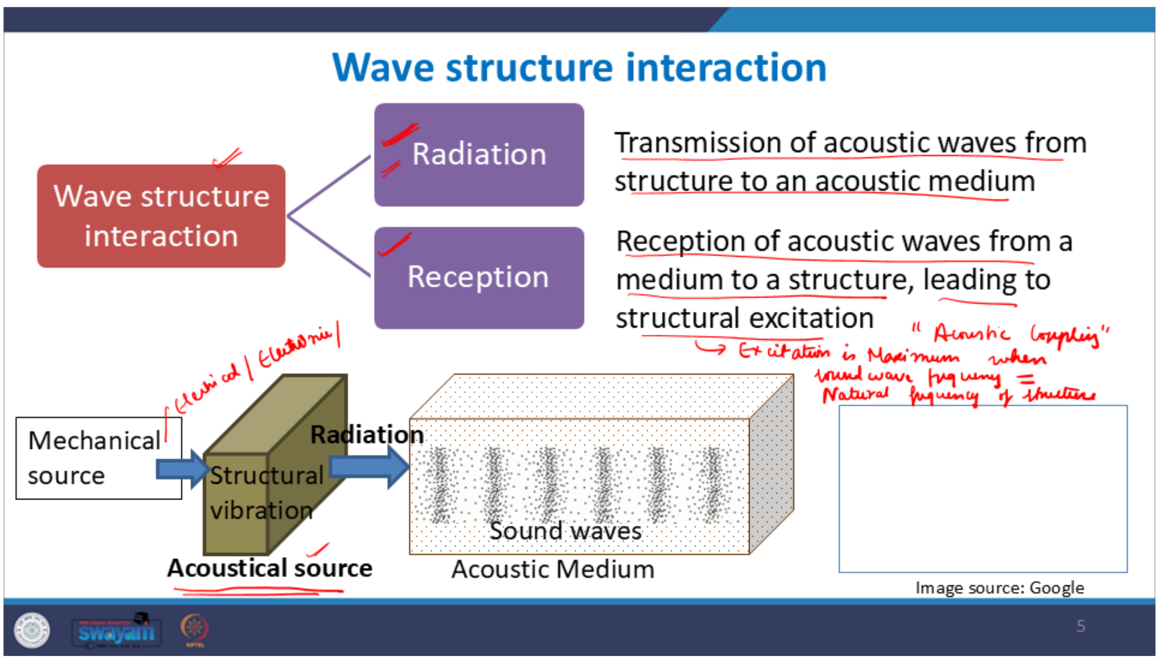
Then we dealt with some special cases for both types of incidence. We also found out Snell's law for wave refraction for oblique incidence where θi and θt are related by the ratio of the speed of sounds in the two media. Now here we'll study about wave structure interaction, as in, till now, we have been studying about what happens when the acoustic waves are propagating in a fluid medium and then they encounter different fluid media. But now we'll study what happens when a solid structure creates the acoustic wave. And then we will introduce the concept of radiation. And then the radiation from some common acoustical sources will be studied where the quality of the radiation, such as the sound field, directionality, source strength, and radiation efficiency, will be dealt with.



So, wave structure interaction.



So, as I told you, here we have seen that in a fluid medium, when the sound waves, which are longitudinal mechanical waves comprising the fluctuation of pressure, or the fluctuation of pressure or the compressions and rarefactions, having periodically sort of propagating in the longitudinal wave fashion over a fluid medium, that is perceived by an ear as the sound wave. These sound waves or longitudinal waves are propagating, and they are propagating in various fluid media and reaching us, but what creates this wave? As in, how these waves are created in the very first place. So, this is where we will study wave structure interaction. So, here we have a solid structure which can vibrate and create the wave and send it over as sound waves. There could be two-way interaction. Either the structure vibrates and generates the sound wave into the fluid medium, or it could be the other way around: there are some sound waves propagating through a fluid medium, and then they encounter a structure, interact with it, and set the structure into motion or excite it. So, let us see.



So, we can characterize this as radiation or reception. The wave and structure interaction, which is the interaction between two separate media solid structure and fluid media in the radiation, here the interaction direction is this way, radiation, and the interaction direction for reception is the other way around. So, for the radiation, what happens here, from solid structure to the fluid medium, we are having this interaction. So, what happens? The acoustic deals with the transmission of the acoustic waves from the structure to an acoustic medium.

Whereas in reception, it is the other way around. Here, the acoustic waves that are already propagating in a fluid medium get received by the structure and lead to the structural excitation. We will study in detail about radiation, but reception is something whose description we will limit in this particular course. So, only here we will discuss it, but the detailed description of reception is out of the course for an introductory course on noise control and mechanical systems. An example of reception I can give you here is that, let us say, in the very first few lectures, I had told you what the mechanism for generating sound.

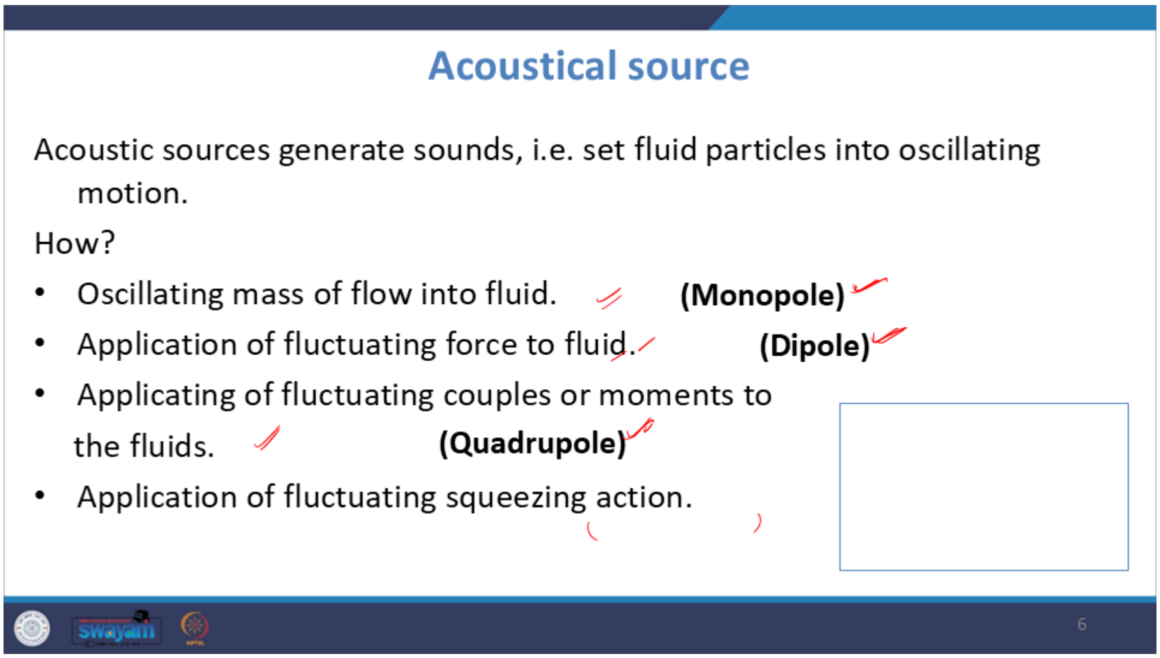
One of the mechanisms is through the vibration of the structure. The other mechanism was through the fluid flow, the example could be a stormy wind which is creating the sound waves. Suppose we have such stormy wind creating the sound waves, and then suddenly, it comes and encounters the roof panels and sets the roof panel into vibratory motion. People who live in very windy areas and have got thin tin-like roof panels usually experience this disturbance that whenever you have a windy weather, the roof panel is set into a vibrating motion and it gets excited. So, sound waves have the capability to excite the structure, and that happens when the frequency of the sound wave matches with the natural frequency of the structure it is exciting. Then we say that the structure and the sound wave or the fluid and the structure, they are getting acoustically coupled.

So, the excitation is the maximum here. Excitation is maximum when the sound wave frequency is the same as the natural frequency of the structure that is receiving these sound waves. Similarly, sometimes you see that due to these heavy flows of winds, the bridges are set into motion, they vibrate, and they can collapse as a result of that. That also is an example of the reception of the sound waves by a structure and resulting in the excitation of the structure. And if the frequency matches and there is acoustic coupling, a perfect acoustic coupling, then it can lead to disastrous results where the structures start vibrating at extremely high amplitudes and they can collapse and break down.

So, now further into this, we will start with a detailed description of the very first phenomenon, which is radiation. So, let us see here; we have got a structure (refer slide 5). Now, it could be set into vibration due to some mechanical source. So, let's say, for example, we have got a gearbox or some kind of machinery component having gears, and the gears are rotating over the shafts. Due to the rotation of the shafts, and some kind of unbalance in the mass, the shaft itself can be set into motion, and any structure that is connected to that shaft will then again be set into vibratory motion. So, due to some mechanical source, it can also be an electrical or electronic source.

The structure can be set into vibration. So, that is not of concern here in this course on noise control. So, due to some source, the structure has been set into vibration. Now, this structure, once it is set into vibration, becomes an acoustical source because now this becomes the source of creating sound waves or acoustical waves. When it becomes an acoustical source, it radiates away the sound waves into the surrounding acoustic medium, and this acoustic medium could be air, water, or even some solids, etc.

So, now these acoustical sources or these acoustic sources, they are radiating the sound waves into the fluid medium. So, they are the source of the sound waves. They can generate sound waves and send the fluid particles into oscillatory motion in various manners. How?



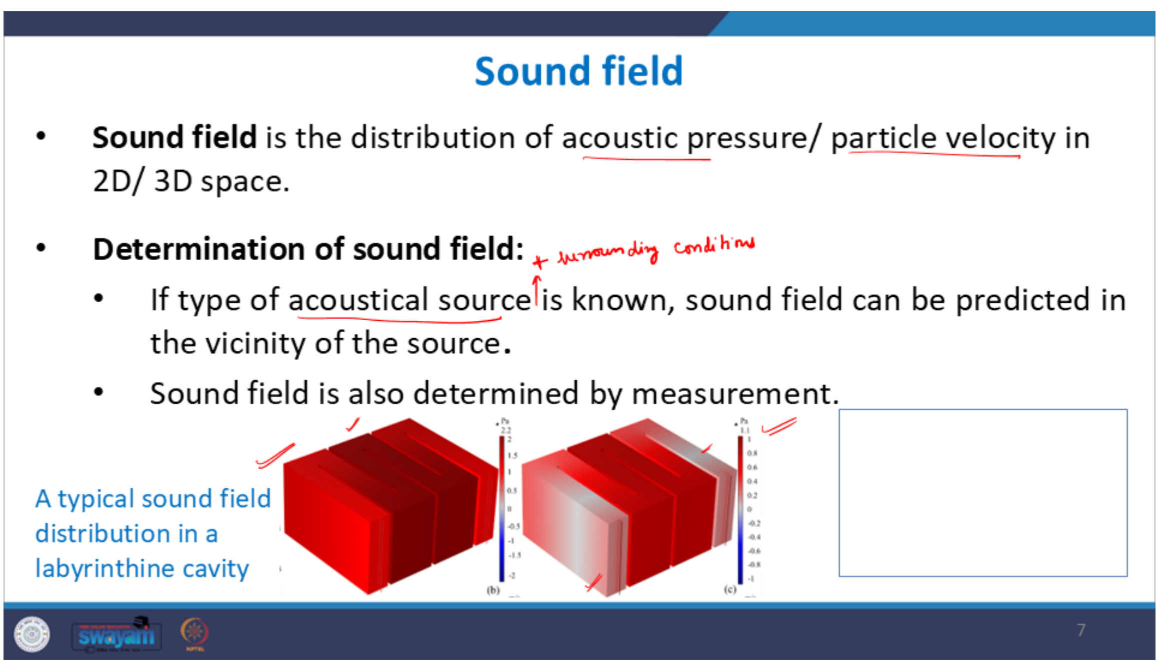
Well, it could first be due to the oscillation of mass flow into the fluid. So, if by some means we have a certain source and it is able to create a mass flow into the fluid medium and back, so mass flow into the fluid medium and back again So, due to the continuous push because of the addition of mass, suddenly there is certain mass flow that is coming into the fluid medium, and due to that, it is pushing the fluid particles away, and when the mass is going in the opposite direction, it is again allowing the fluid particles to come back. So, in that way, it is setting the fluid particles into an oscillatory motion.

Or it could be due to some force that is acting, so let us say, for example, I have this hand here, or you can have a tuning fork or anything where you continuously start to forcefully flap it or something, then this motion itself can create sound, provided you are creating the sound at sufficient speed. If I do this motion very slowly, what happens if I am slowly moving it? Sound waves are not being created because I am trying to push the particles here, then they are getting sufficient time to move around. I am pushing them, the particles are moving around, then I am pushing backwards, the particles from here are moving around. They are getting sufficient time to sort of relocate and be at peace, as you can say. But if the frequency with which I am vibrating my hand, or the speed frequency, which is the number of cycles I am doing per second, becomes high enough, then you would be able to hear the sound. You know that a human hears sound from 20 hertz to 20 kilohertz.

So, above 20 hertz, which is So, first I am trying to fluctuate this hand which is more than 20 cycles per second, that it is not even visible properly to the naked eye. So, what happens is we are vibrating at a very high speed, then the fluid particles around it are not getting sufficient enough time to sort of relocate and adjust, and therefore, they are now set into this oscillatory motion, and they are propagating the sound waves forward. Other means of creating sound could be the use of fluctuating moments or couples, which usually happens in the case of turbulence where you have some kind of couple or moment which sets an oscillatory motion to the fluid particles. Then, there could be fluctuating squeezing actions.

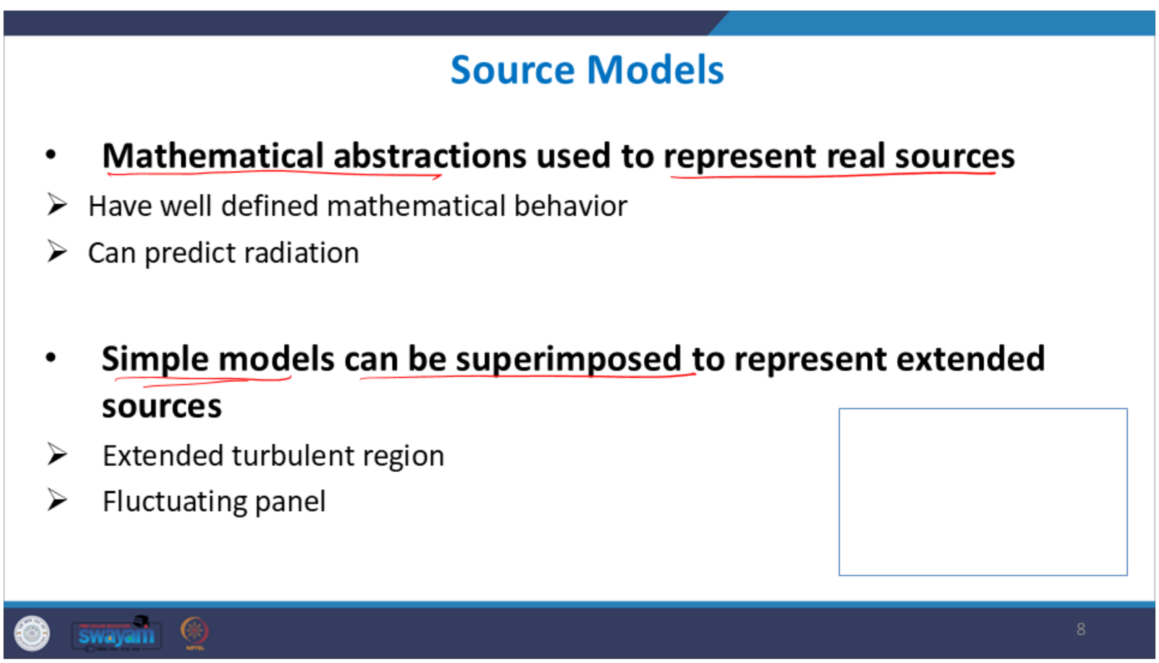
So, depending on how a source generates the sound, we classify them as monopole, dipole, or quadrupole. This particular thing here is a more complicated mechanism, which again we will not deal with in this particular lecture series.

Before we start discussing the radiation due to these typical sources or due to these typical mechanisms. One way to find out how the radiation is happening or to evaluate the quality of the radiation could be through the use of a sound field. What is a sound field?



It is simply a 2D or a 3D graph that shows the distribution of an acoustic variable in space. So, it could either be the distribution of acoustic pressure or the particle velocity in the 2D or the 3D space. This is a typical sound field distribution in a labyrinthine cavity. This figure is taken from our own research work, which has already been published in the paper. We had developed a labyrinthine cavity, and we were observing the sound pressure level distributions across it. Using such kind of contour plots, we can come to know that, okay, here we have the region of high pressure, here we have the region of low pressure, and so on. So, it is a variation with respect to space. How do you determine the sound field for any particular radiation? You either know the source; suppose you know what source is creating the sound wave and under what conditions, whether it is a free-field condition where you have an open space or it is where the source is located in a closed reflective environment. So, you find out what the conditions are: the acoustical source plus the surrounding condition. Whether it is a reflective medium, whether it is a closed room which is reflective in nature, or it is an open field with no reflectors.

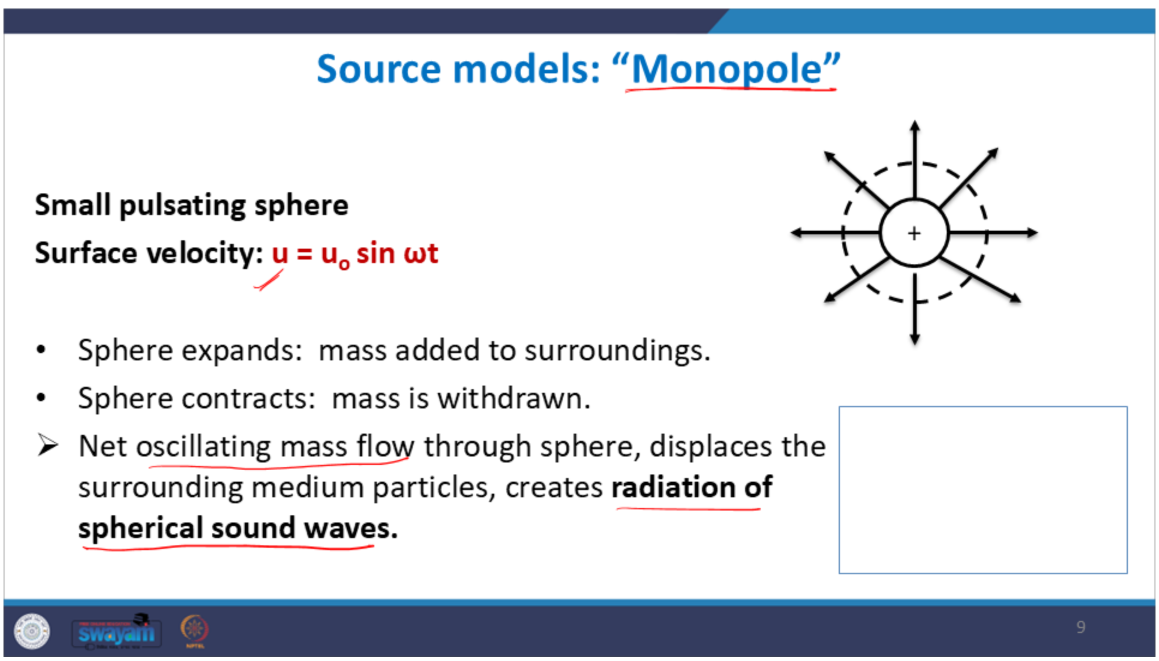
If you know these things, you would be able to predict what the sound field would be like. On the other hand, in real life, if you do not know these things and there are a lot of other unknown variables as well, then you simply measure the sound pressure level. at different points and construct a 2D or a 3D contour to find out what the sound field is like.



Now, let us begin and see some source models. Now, I told you that when there is a structure set into vibratory motion, it acts like an acoustical source, creates sound waves, and radiates them into the surrounding fluid medium.

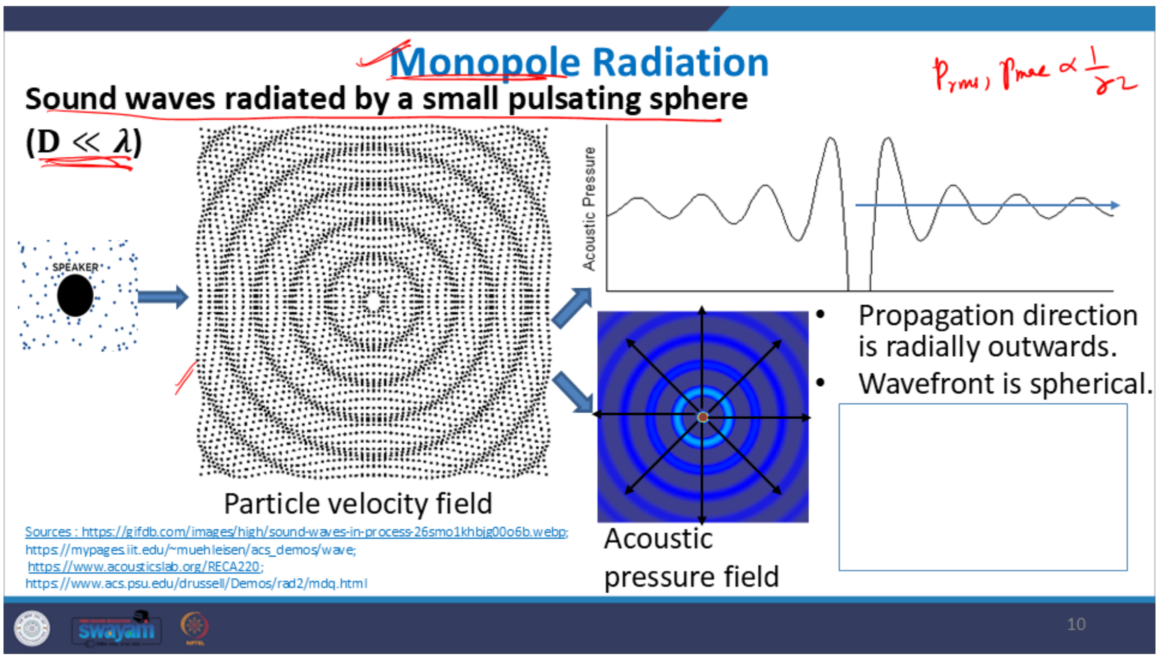
In real life, we have very complicated sources. But dealing with such complicated sources, because each source could be different from the other, is very impractical when you do a theoretical analysis of such sources. Therefore, we need some kind of mathematical abstractions that could be used to represent these real sources. So, which means that we can have some very simple sources whose behavior we can fully analyze theoretically, and we can create a model of the radiation. Then, the real source could be represented as a superposition of these various simplified sources. So, what are these simplified sources and the models that we study?

that we will study. So, basically, the simplified models can be superimposed to create more extended real sources.



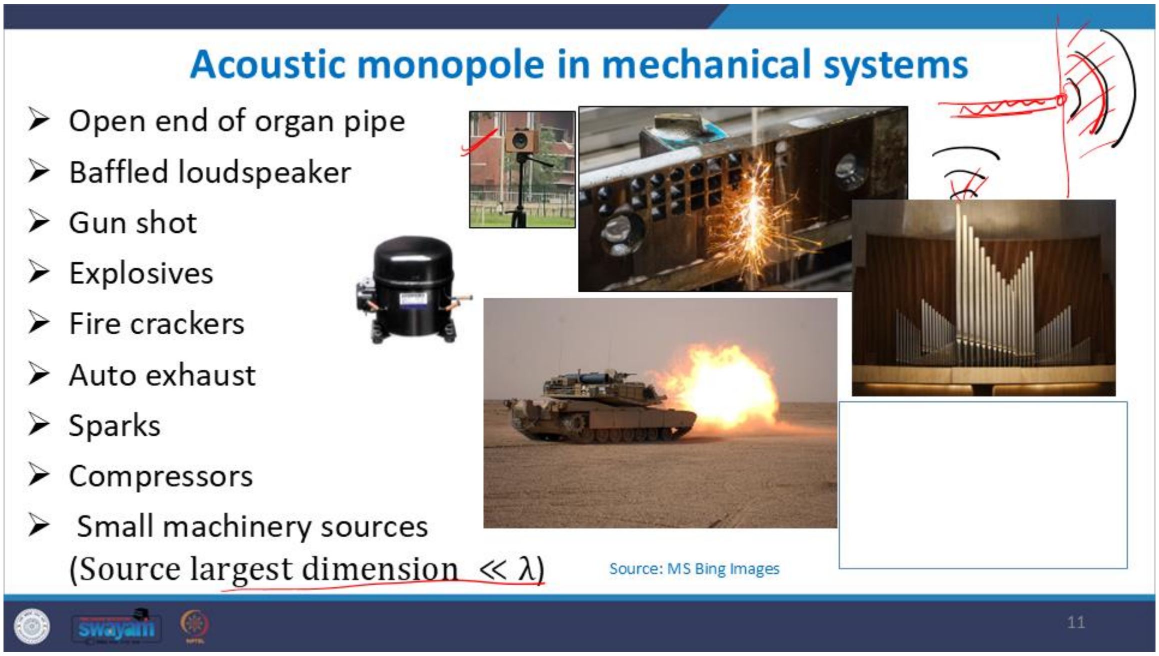
So, let us study these simplified source models. The very first source model is the monopole. So, what do you mean by a monopole or an acoustic monopole?

An acoustic monopole means it behaves as if it is a point source. So, a very small spherical source or a small ball of mass. Which is pulsating in the atmosphere, meaning that the ball is expanding, contracting, expanding, contracting, and doing so at a very high speed, high enough to create sound waves. Let us say the surface velocity is something u. Here, this is the source. What happens here is this ball or sphere, or this spherical mass, is expanding, which means that it is adding certain mass to the surroundings and pushing the fluid particles away. Then, when it is contracting, it means that it is withdrawing the mass from the surrounding fluid medium, and the fluid particles now have more room or more space, so they come back. And therefore, this is the net oscillating mass flow which creates the radiation. And what is the radiation of such a monopole? It is the spherical sound waves. We have already studied spherical sound waves, cylindrical waves, plane waves, and so on. So, the monopole creates these spherical sound waves.



So, some animations just to illustrate this phenomenon. Now, I told you in the previous lectures also that you get a spherical wavefront when the source is like a point source, which means that the largest dimension of the source is much smaller than the wavelength under consideration. So, under these conditions, the source can be thought of as a monopole. And it radiates. So, you can see this ball or sphere trying to move the particles and setting them into oscillatory motions, and you are getting this kind of spherical wavefront.

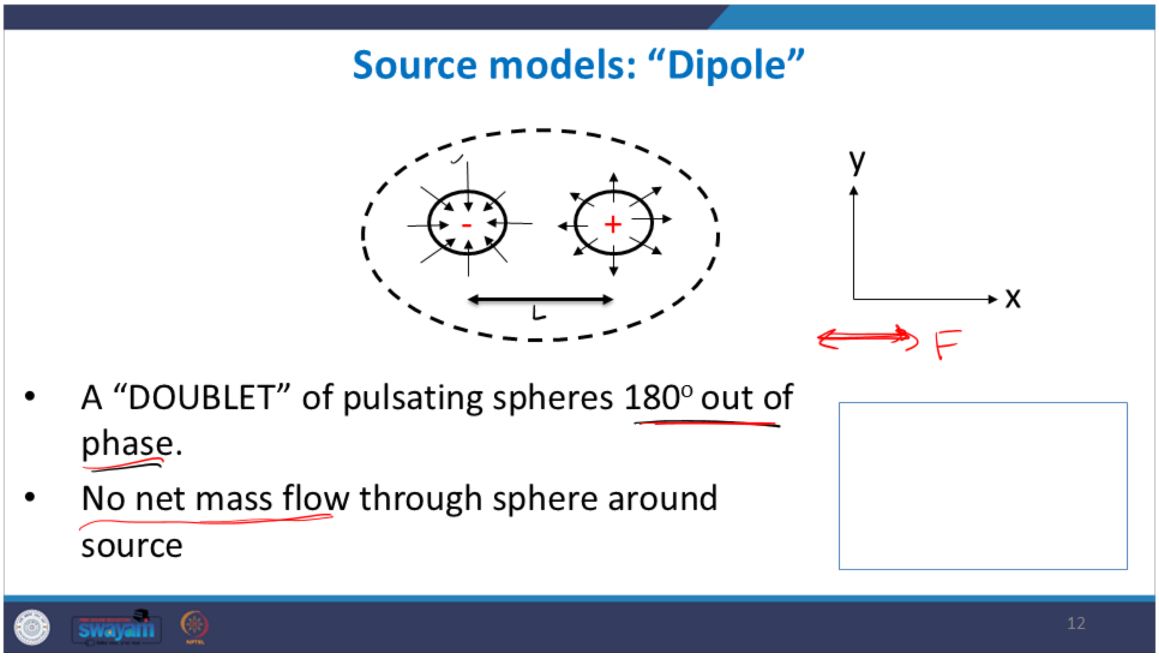
For example, if there was a still lake and you dropped a small pebble into the water, what happens? You see the ripples of waves that are radiating or the ripples of waves that are coming out uniformly in all directions from the point where you drop the pebble. And they are creating these spherical waves that are moving forward. So, it is very similar to those ripples of waves radiating uniformly, okay? And we have already studied about the spherical wavefront and how it attenuates over space. We know that the P_{RMS} and the P_{MAX}



They are inversely proportional to the square of the distance. So, it is the inverse square law that they follow, and some of the sources which we have already discussed for the spherical waves, they all behave like acoustic monopoles. You can have a baffled sound loudspeaker or a speaker that is boxed. So here, what happens is the diaphragm of the speaker is moving, and it is boxed from all the other sides and installed inside a box. This diaphragm moves; it essentially is like mass flow into the fluid medium and retraction, mass flow into the fluid medium and retraction. There is a mass addition. Suppose the box is fixed, and we have the diaphragm that moves. It is increasing the mass and then decreasing, increasing the mass and then decreasing. It is sort of creating a mass flow into and away from the fluid medium.

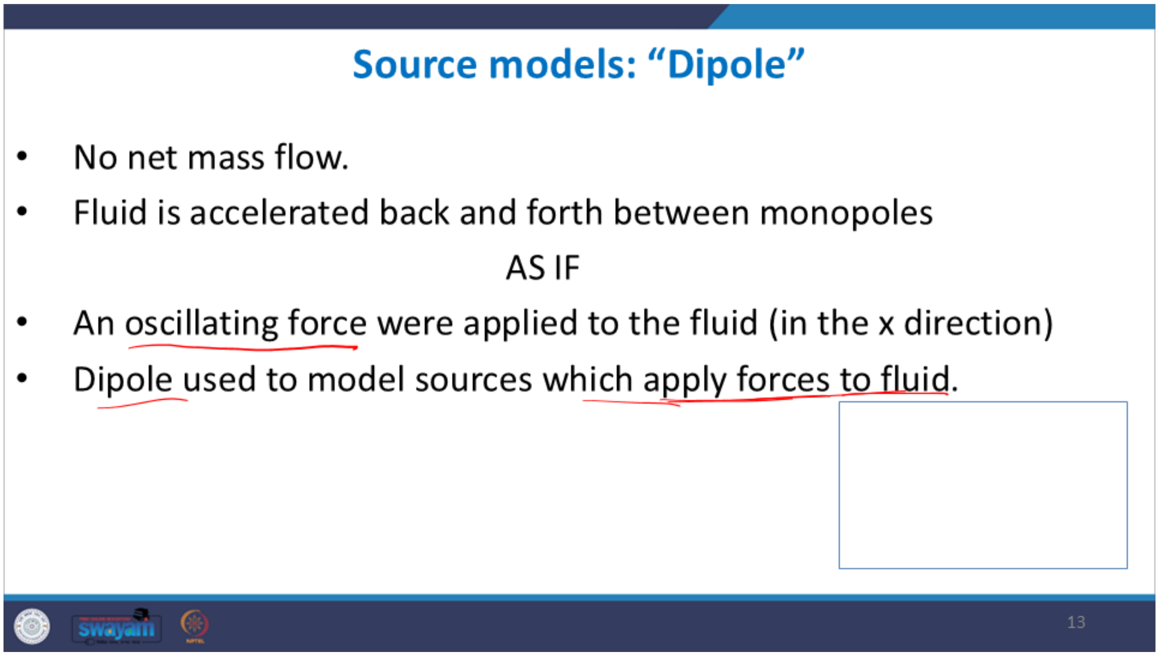
Then we have things like gunshots, sparks. Then the exhaust coming out from the tailpipe at the very end when it encounters the infinite baffle of the atmosphere, the small compressors, then other such small machinery sources, even the open end of an organ pipe. So, whenever you have a long pipe, inside this, the sound can have any kind of waveform. For example, in the tailpipe it can have a harmonic plane wave, but at the very end when suddenly this small source is encountering an infinite baffle in the form of open atmosphere, the waveform becomes spherical in nature.

So, this happens with the end of the tailpipe where you have the exhaust coming out into the atmosphere and the sound coming out from these open ends of the organ pipe. So, explosives, firecrackers, all of these, they become the acoustic monopole. So, you have a lot of sources which behave like this.



Now, what do you mean by a dipole? That is a second source model. So, imagine two monopoles that are kept together, separated by a small distance. Let us just call it some distance L. So, these two monopoles are separated by a small distance and, most importantly, they are antiphase. So, 180 degrees out of phase.

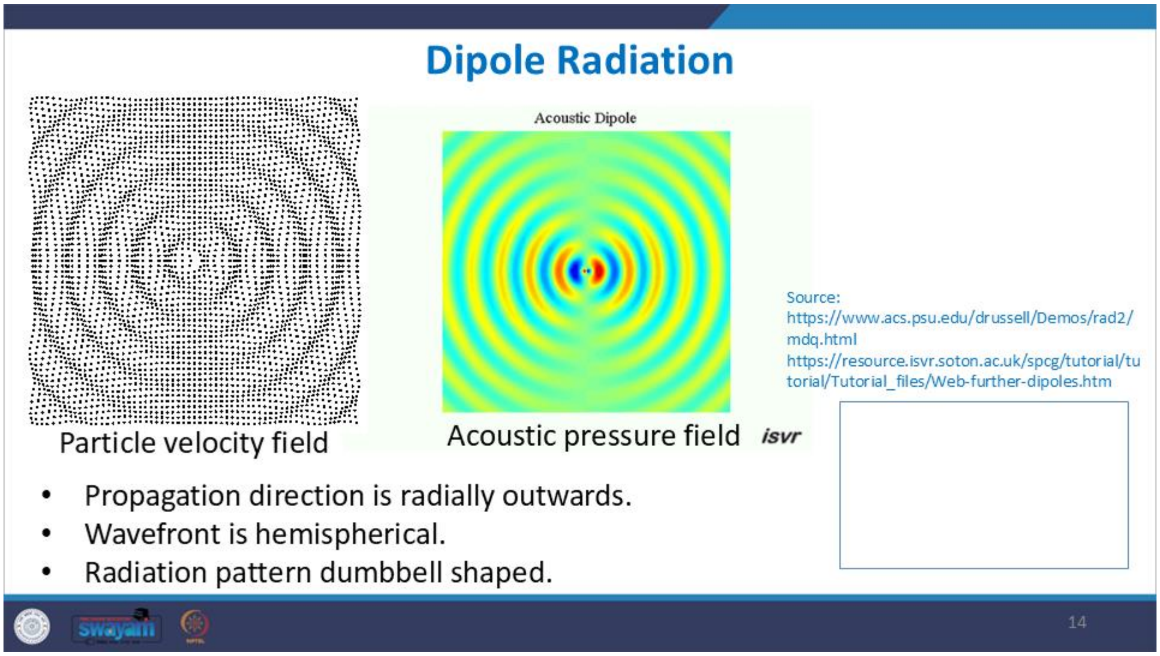
So, what happens? So, that essentially means that if, suppose, we are representing them as a ball of mass that is expanding and contracting, each monopole. So, there are two. Imagine two balls of masses: when one expands, the other one contracts, and when the other one contracts, the first one expands. It's this kind of motion that happens. So, if you see, when you take them together, the amount of mass that the first ball is adding is that same amount of mass this one is sort of subtracting from the medium? So, there is a certain mass in the fluid medium, but there is also a certain mass that is coming back into the ball. So, overall, the net addition of mass is zero at any moment in time. If there is some addition, it is nullified because of the contraction of the other sphere and vice versa. So, there is no net mass addition when they are considered together.

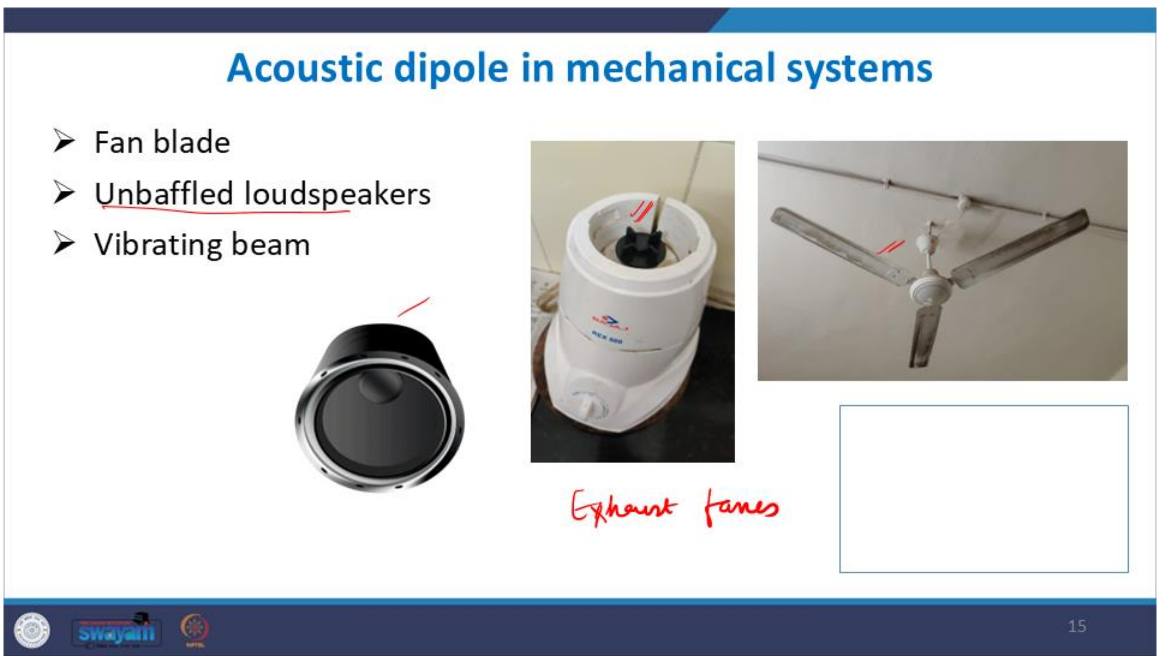


But there is a force that acts. So, here it is not due to a net mass flow, but the sound generation is actually due to an oscillating force that is creating it. So, here, if this was a positive x direction, it behaves as if there is a force acting, an oscillating force F acting in the x direction and moving the fluid particles. It is equivalent to, if you have a thin panel or a hand that's fluctuating rapidly, it's not essentially adding any mass to the atmosphere or removing it. The mass is the same. It's creating a force that is sort of pushing the particles away or oscillating them. So, various kinds of sources that behave this way, which apply forces to the fluid in a fluctuating manner, they behave as a dipole

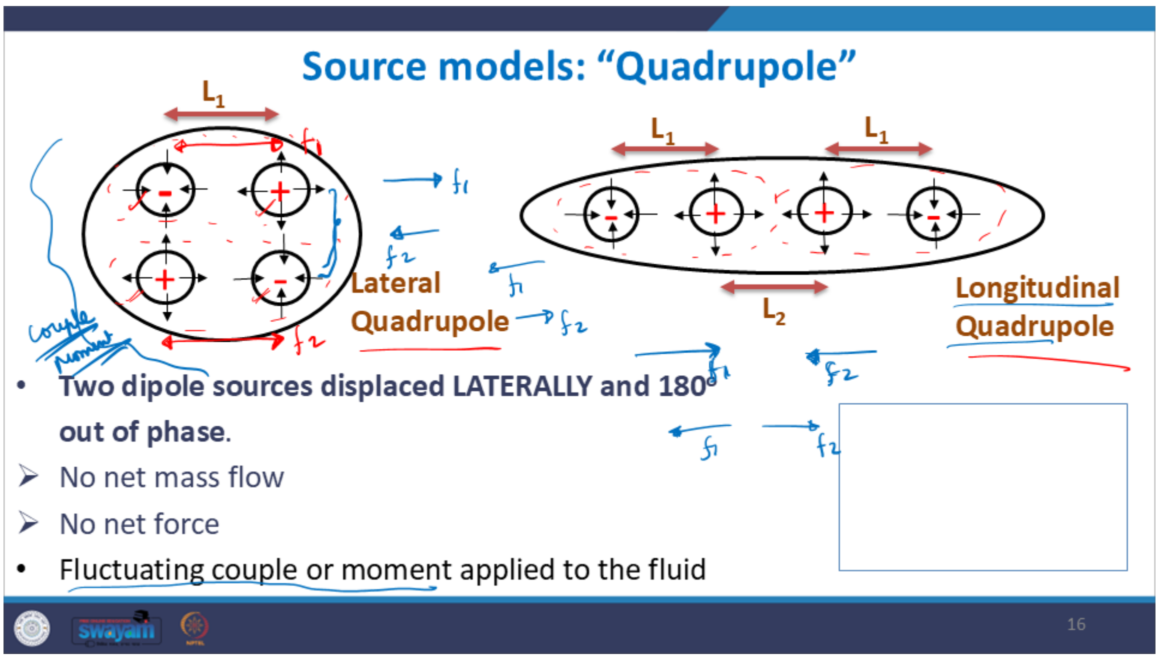
Now, this shows us (refer slide 14) the particle velocity field for a dipole. In a previous case you had uniform ripples all around, spherical in nature, but here what you observe is that there are two ripples, antiphase to each other, hemispherical in nature.

This shows us the acoustic sound pressure distribution and the radiation pattern for this one would become dumbbell-shaped like this. And there would be a region here where the sound pressure would be nullified. More on that in the subsequent slides: some examples of acoustic dipole. We have got now these are some of the pictures taken from my own household (refer slide 15). I just went around looking into my house and seeing, what could





be the typical noise sources that could be represented as an acoustic dipole. So, any kind of fan cutting motion, the fan that is moving away, it is not essentially adding the mass; it is cutting the fluid through sudden force and oscillating force. So, here the noise radiating due to this mixer grinder because here essentially, we have a fan that is rotating, the noise due to the ceiling fans, the blowers, exhaust fans. So, any kind of such fans, they usually behave as an acoustic dipole. And suppose you have a speaker that is not boxed; it is open, so the diaphragm is open. So here, what happens when it was boxed? So, these sides became fixed, and the diaphragm was moving like this, but now when this is removed, it's an open diaphragm speaker, then it behaves like this. So essentially, when this is moving, this is contracting. When this is contracting, this is moving. No net mass flow but rather an oscillating force. An unboxed speaker behaves like a dipole. Then various kinds of vibrating beams as well behave like dipole.

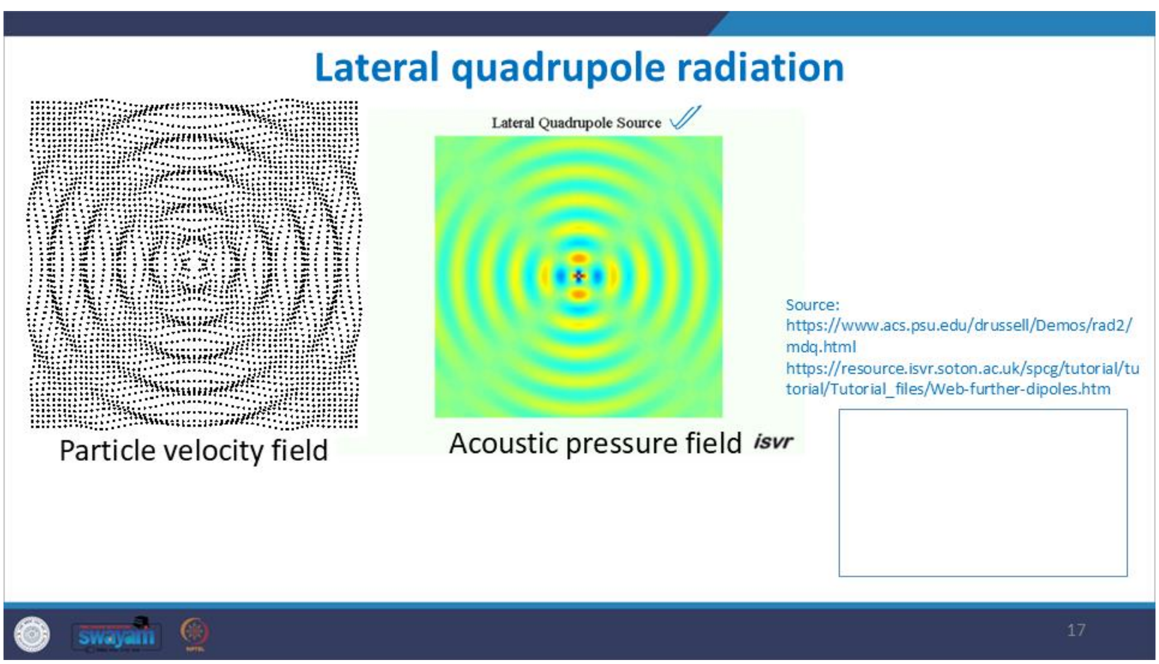


Now, the last type of source which we will see would be a quadrupole. So, as the name suggests, it is composed of four monopoles. There are two types of quadrupoles we can create. One is the lateral, and the other is the longitudinal one. In the lateral, what happens? Imagine that it is like one acoustic dipole here. Another acoustic dipole here, and they are antiphase with each other. So, they are placed one on top of another, and in the case of longitudinal, all four monopoles are in line. So, here, this makes one dipole.

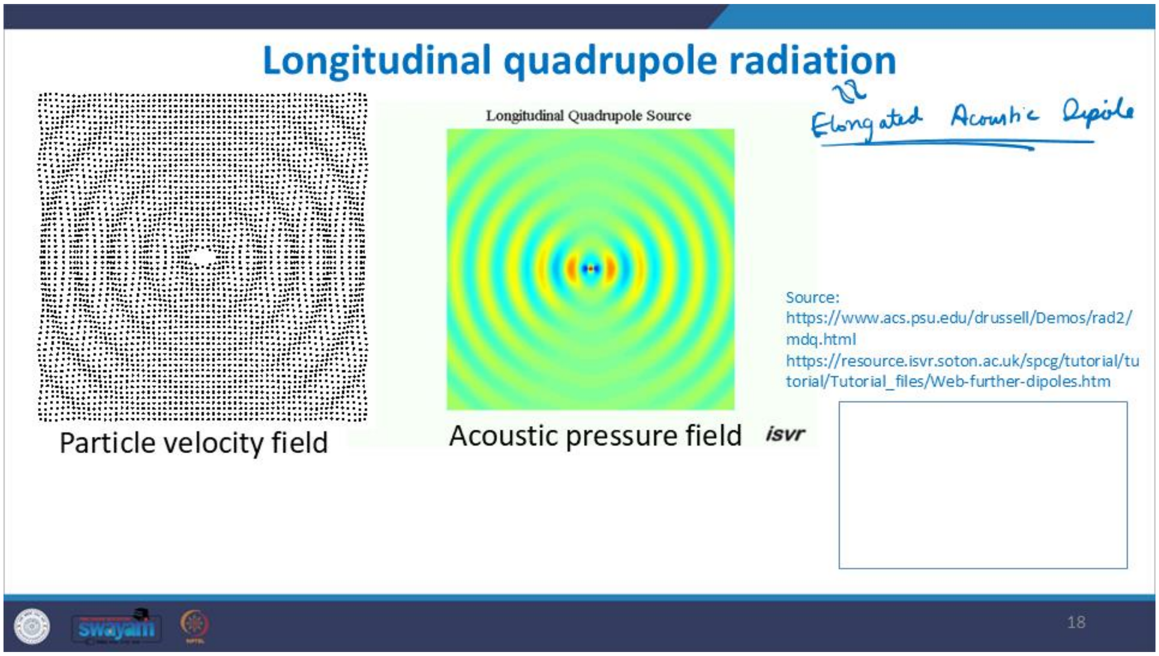
This makes another dipole antiphase with each other, and they are along the same line. So, in both these cases, what happens is that the net mass addition is 0 because, whatever is being added by this pair is getting canceled by this pair, and whatever is added by this pair is getting canceled by this sphere (refer slide 16). And so on, no net mass addition is happening, but at the same time, there is no net force because, suppose here, there was one force acting along this direction, and this force is also acting along this direction, F1 and F2. So, now, F1 and F2 are what?

Their force is due to these individual dipoles. Because the dipole is placed antiphase. So, when this is plus, this is becoming minus, which means plus here means expansion of the sphere, and minus means contraction of the sphere. So, they are placed opposite. So, which means that when F1 is in this direction, F2 is always opposite to it, and when F1 is here, F2 again is opposite to it. It is like two equal and opposite forces. Separated by a certain distance, this one So, a certain distance they are separated by. So here, what is that? Two forces, collinear, separated by a distance, equal and opposite in nature. No net force, but they actually create a moment or a couple. So, that is the mechanism for sound wave generation. The same here, what is happening here is that the force F1 is here and the force F2 is here. What we see is that we get a couple or a moment. But if you look at the longitudinal dipole, what do you observe?

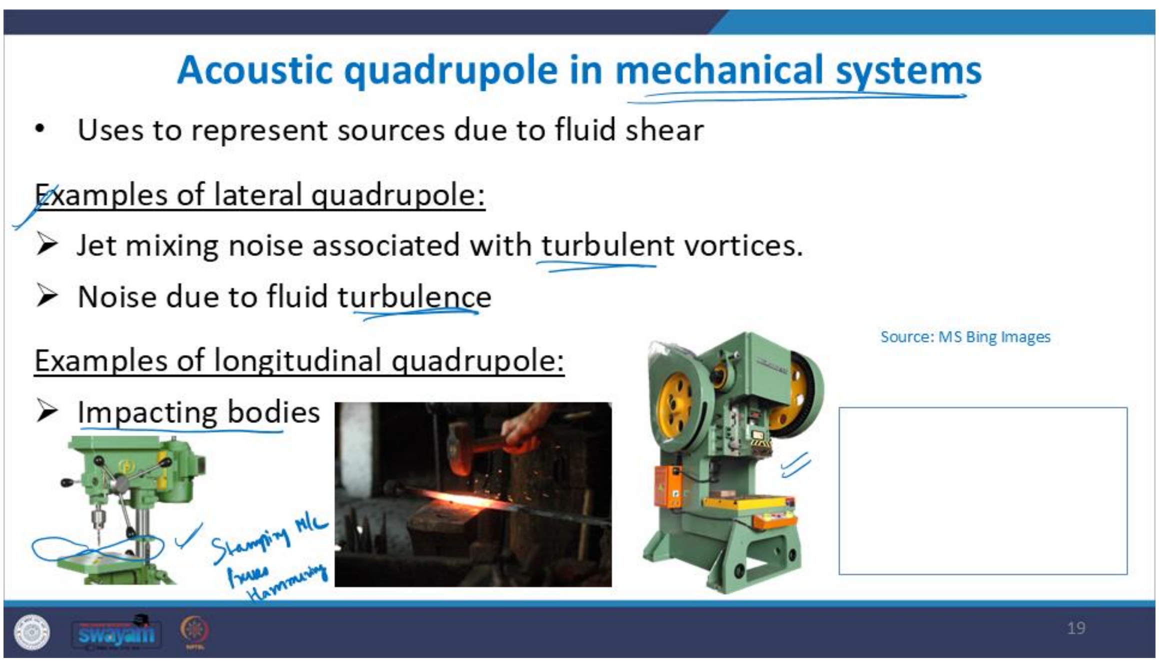
You have a net force F1 and the net force F2 in this direction. So, when F1 and F2 are equal and opposite, and again F1 and F2 are equal and opposite. So, there is no net addition, but these forces are collinear. Does it mean that there is no net force, no mass flow, nothing? No. They are collinear, and there is no net force addition, but it behaves as if it is a peculiar case where what happens is that this longitudinal quadrupole behaves as if it is an elongated dipole. Let us see their particle field distribution and radiation patterns.



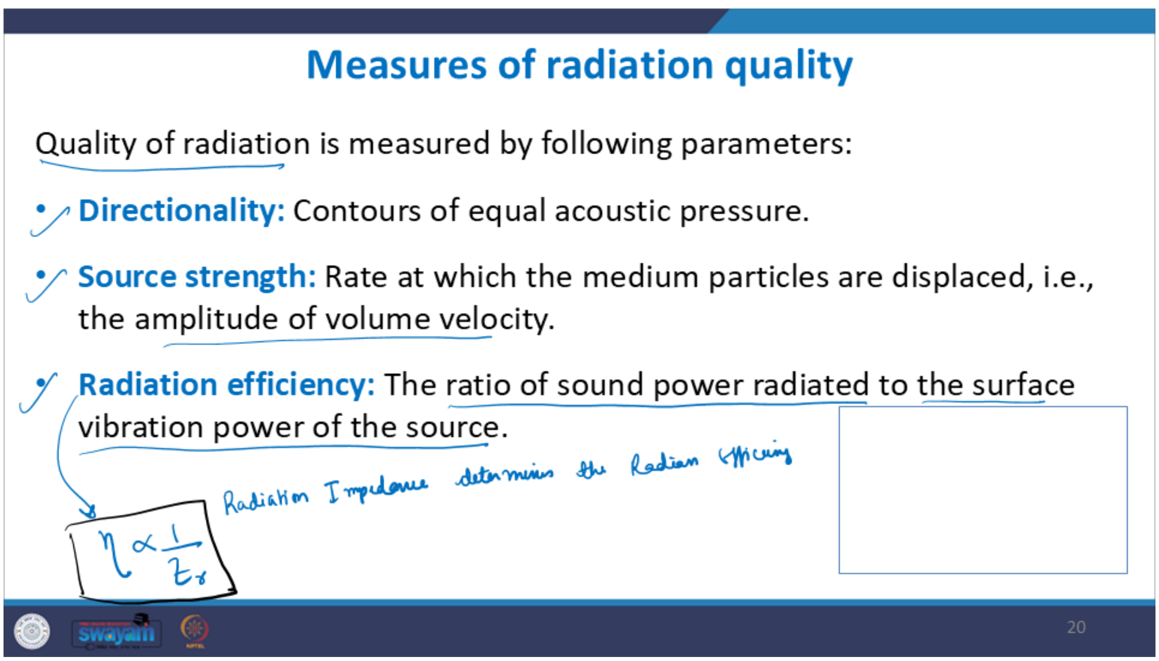
This is for the longitudinal. So, it is like 4, you cannot say hemispherical, let us say quarter spherical, 4 quarter spherical ripples coming out, all antiphase with each other. This is the typical sound source field; this is how it looks like. For a lateral dipole, for a longitudinal one, the particle field is quite similar to the acoustic dipole.



It is like an elongated. Very much like an elongated acoustic dipole and a similar kind of field and radiation pattern.



Some of the sources of acoustic quadrupole are, when you have jet mixing noise associated with turbulence, noise due to fluid turbulence; all of these are examples of lateral dipoles or turbulent noises. Whereas, for longitudinal quadrupole, which behaves like an extended acoustic dipole, you have impacting bodies. For example, here you have a machine, various kinds of, you know, sheet metal cutting machines, various kinds of industrial presses, the stamping machines, the coining machines where, you have cut, cut, cut something like that; you have the, you know, impact coming up of the bodies, then it is creating a longitudinal dipole like this, and the sound field radiates in the same way. You have got an ironsmith that is trying to hammer and shape a rod; then you have these industrial presses and pressing machines, so pressing, stamping machines, so many things like that. So, you have the stamping machines, the presses. You know, hammering all these actions or mechanical systems, they generate; they behave as an acoustic quadrupole. So, you get a lot of acoustic quadrupoles in mechanical systems.

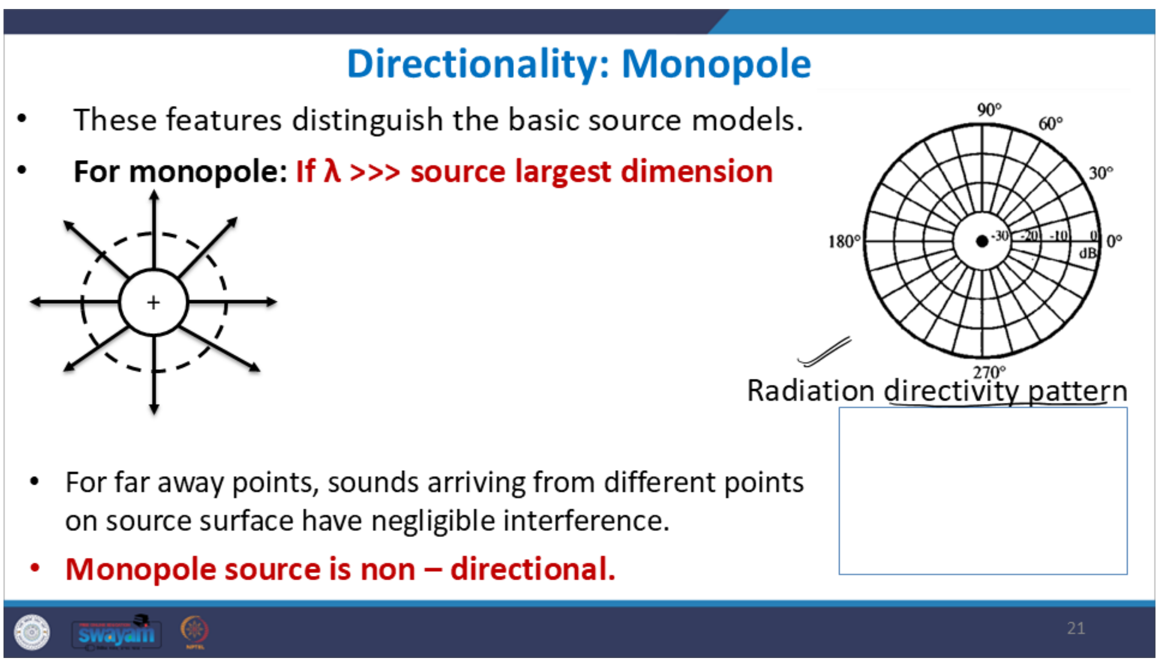


So, we studied about the different simplified source models; then now we will measure the radiation quality. How do you, you know, sort of differentiate the radiation pattern of these sources? You can differentiate it using these three factors. So, the quality of radiation can be differentiated using this. The first is the directionality, which is the contour of equal acoustic pressure. Then the source strength; it is the rate at which the medium particles are being displaced.

So, the rate at which they are being displaced is simply the rate at which a volume of the medium particle is being displaced; that could be a way to put it. Then, radiation efficiency, which is the ratio of sound power radiated to the surface vibration power of the source. Now, if you remember when we were studying about acoustic impedance, I had introduced a term called radiation impedance. The radiation impedance determines the radiation efficiency. You can say that the more impedance it has, the less efficient it is. So, suppose we indicate the radiation efficiency by the symbol eta; then this eta would be inversely proportional to the radiation impedance Zr for a source,

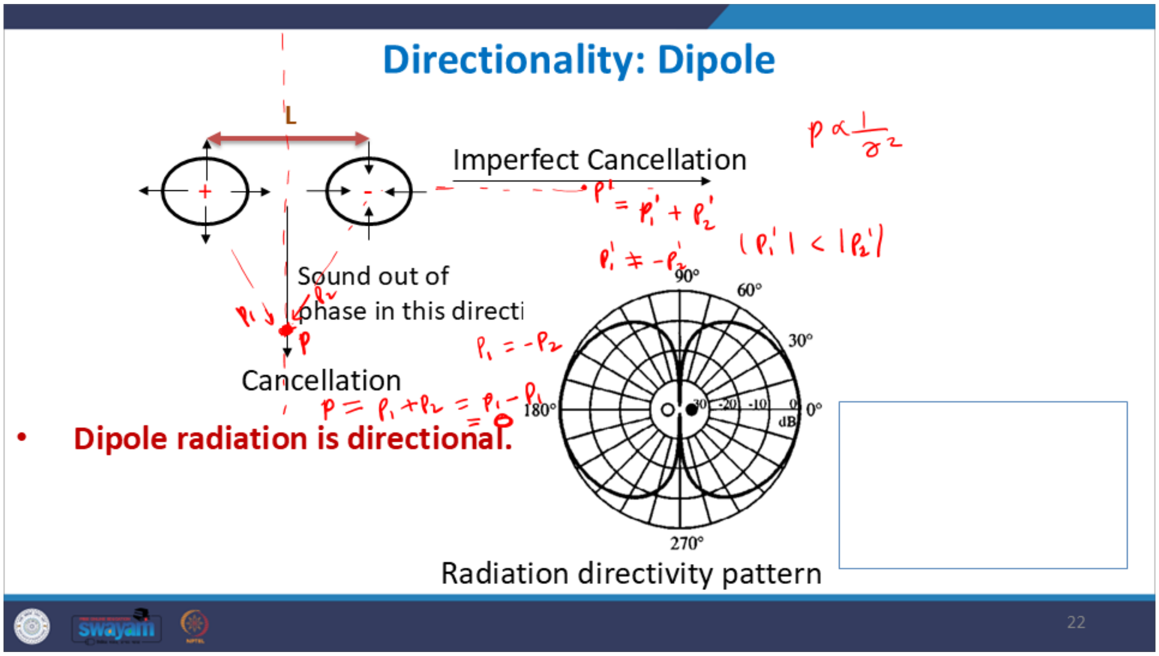
$$\eta \propto \frac{1}{Z_r}$$

It is the ratio of the sound power that is being radiated to the vibration power of the source. It is sort of the ratio; it is the conversion of power from vibration to acoustic waves. It is how much, what fraction of the vibrational power is actually used up in radiating and creating the sound waves.



So, directionality; let us see these features for the different basic source models for a monopole because it is uniform throughout. You get a spherical kind of directionality pattern, which means that, provided the source is in an open field environment and there are no obstructions in the way. The contours of equal pressure will always be spherical in nature.

So, quickly I would refer back to the radiation pattern (Refer slide 10). So, you see here for a monopole over here; these are what? All of these are spherical waves that are propagating forward. So, spherical waves where each pair corresponds to the particles of the same amplitude and the same pressure. So, you are getting a uniform radiation pattern. Or directivity pattern.



Now, what happens in the case of a dipole is that if you see along the line that is a perpendicular bisector to these dipoles. So, it is perpendicular to the axis of the dipoles and located exactly midway of these dipoles. Whatever sound is being added due to this that same sound is being removed because of it. Which means that they are antiphase to each other. let us say there was any point P in this particular line, then there would be a perfect cancellation because P would correspond to There is some sound wave P1 due to this and another sound wave P2 due to this. So, P would be an addition of P1 and P2, but they are antiphase to each other. Because they are antiphase to each other. whatever pressure is due to the first monopole is minus the pressure due to the second monopole. So, essentially this P1 minus P2 would be minus P1 minus P1. Ultimately, the pressure at all times is 0.

$P = P_1 + P_2 = P_1 - P_2$=0

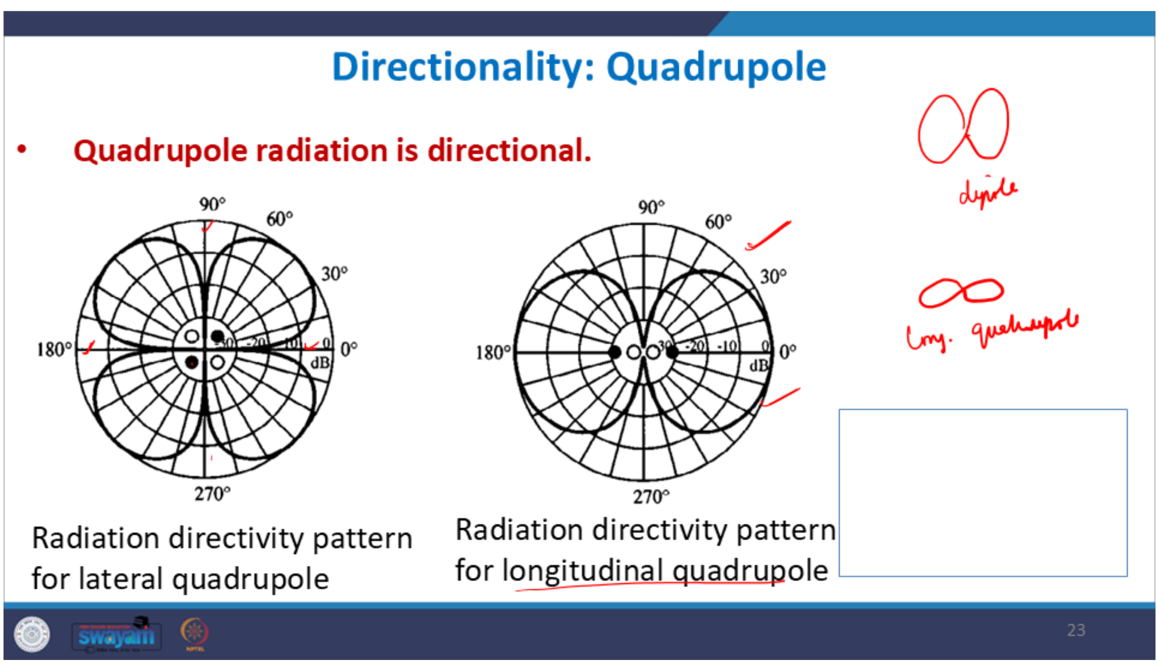
So, there is a perfect cancellation in this particular line, which is midway between the two monopoles and perpendicular to the axis. Whereas, in here there would be imperfect cancellation because although here also you have a certain pressure p' acting, but what is happening? This P dash is again due to the first monopole the pressure due to first monopole plus the pressure due to the second monopole, but here P_1' dash is not equal to exactly this thing, because the distance between the two is changing here. The waves that are coming from the first monopole are traveling through a higher distance and the waves coming from the second monopole are covering a smaller distance, and the pressure is inversely proportional to the distance being covered.

$$P \propto \frac{1}{r^2}$$

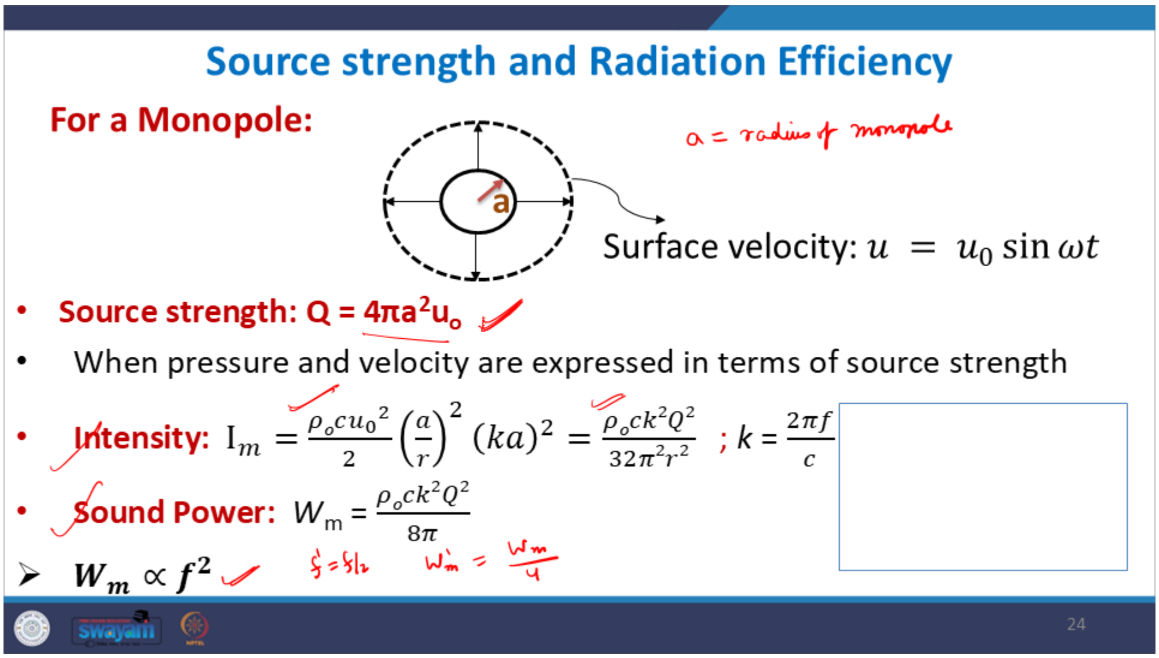
So, here in this case what is happening is that

$$|P_1'| < |P_2'|$$

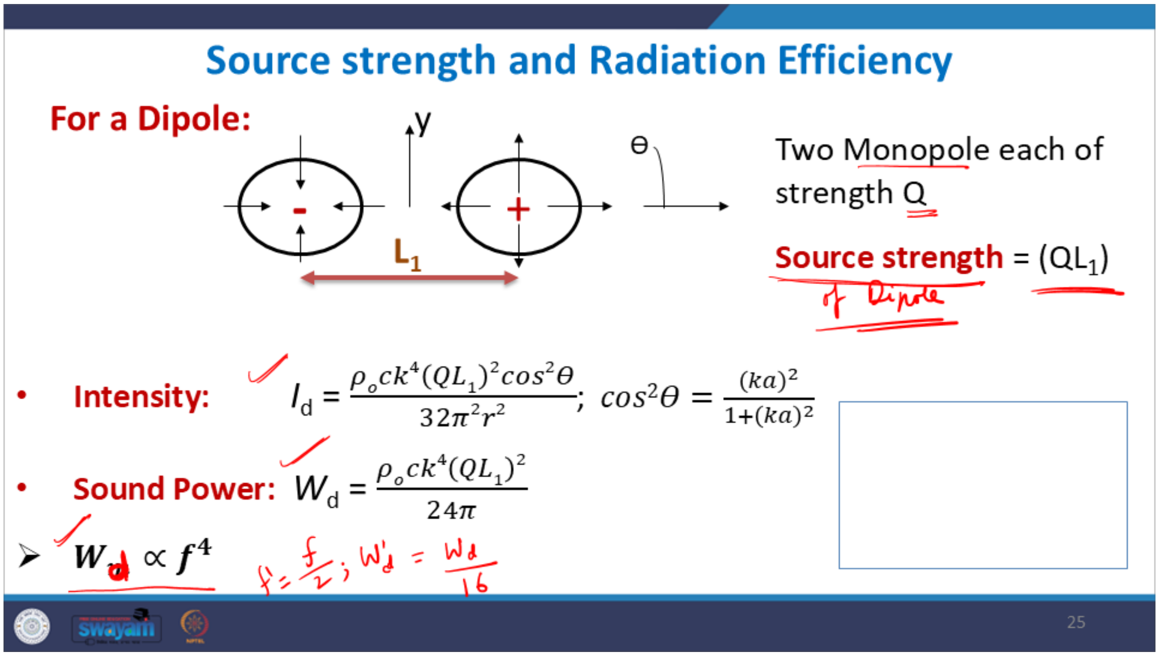
the $|P_1'|$ would be smaller than the $|P_2'|$. So, imperfect cancellation happens. So, ultimately this is the type of radiation pattern that you get. Let me sort of erase this for it to be visible clearly. You see here what happens is that there is a cancellation along this line, and then there is a two-double-shaped hemispherical pattern for the quadrupole. By the same logic, in a quadrupole.



There is a cancellation in this line as well, and there is also a cancellation in this line. Due to this, two dipoles are there. So, due to this, we have these four, zero lines, and then we have got this small, radiation patterns, okay. So, double-double shaped sort of. And the directivity pattern for a longitudinal quadrupole behaves like an elongated dipole. So, it is very similar to a dipole directivity pattern. The difference is that here the width is decreasing. instead of having something like. Here, what happens is it is sort of shrinking in nature. That is the kind of radiation pattern here. if this was a dipole (refer slide 23). Then for a longitudinal quadrupole, it would shrink compared to the dipole.



Now we will quickly see the source strength and the radiation efficiency for a monopole. The source strength Is simply the volume velocity as already defined. Suppose it is moving with some velocity u, then the source strength is simply the volume velocity, which means the velocity multiplied by the surface area. This is what you get. This is the amplitude of the volume velocity, the surface area multiplied by the amplitude of the velocity that will give you the source strength, then the intensity, and the sound power for this. This is a long expression; the derivation is long, which we are not dealing with in this course. So, directly, I am putting away the expression here (refer slide 24). This is the expression of the intensity and the sound power for these sources in terms of A, being the radius of the monopole. So, as you observe here, this Wm is directly proportional to the frequency square. which means that as frequency increases, the amount of energy it is radiating would quadruple. It would be increasing two full times. If the frequency doubles, then the radiated energy quadruples, and so on.



Now, this is for an acoustic dipole. It can be considered as composed of two monopoles, and the strength of each monopole is the same

$$Q = 4\pi a^2 u_0$$

the surface area multiplied by the amplitude of velocity. And then they are separated by a distance of L1. The source strength of the resultant dipole is given by q times L1.

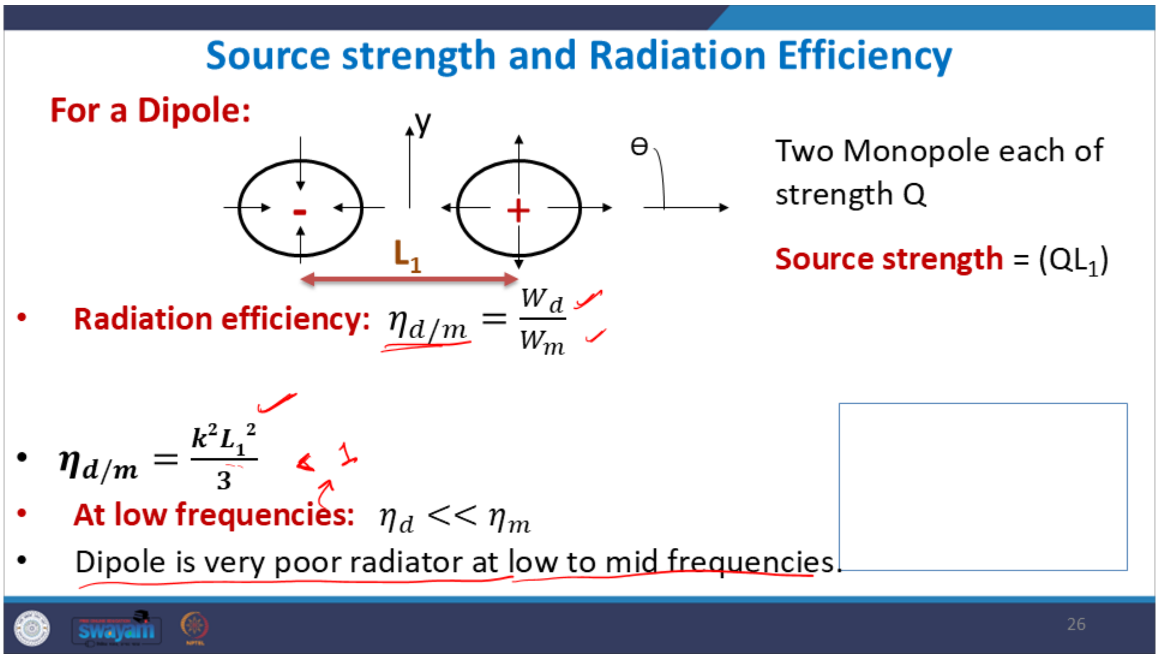
The intensity, this is a long expression. For intensity and the power directly, and what you see here is that here it increases as the fourth power of the frequency. So, from here, one implication, or one, sort of inference you can draw, is that suppose f is very small, it is going to affect the radiation of a dipole much more compared to the radiation from a monopole. Because suppose you decrease the frequency, then the energy would decrease almost the fourth power of whatever frequency decrease you are observing. for example, let us say the frequency decreased by 2. So, this will say that d. So, this one correction here, this is w due to d. So, this wd (refer slide 25) would become if

$$f' = \frac{f}{2}$$

then

$$W_d' = \frac{w_d}{16}$$

Whereas, in the case of a monopole, if you had reduced your frequency, then the new energy would be the old energy times 4. So here, the decrease of the frequency is having more effect on the dipole; it's more sensitive to such frequency changes.



Then, if you calculate what is the radiation efficiency of a dipole with respect to a monopole, that's what $\eta_{d/m}$, which should be we can directly compare because both of them are having the same volume velocity and the same vibration power. Then, we directly compare the sound energy that is radiated by a dipole and its respective monopole, and you can see it over here. Let us say this is the dipole sound power, which is

$$W_d = \frac{\rho o c k4(QL1)2}{24\pi}$$

$$W_m = \frac{\rho o c k2Q2}{8\pi}$$

So, this term cancels out. Here we have k^4. If you divide it, k^2 remains and L_1^2, the new factor comes in, and $24/8$ is going to be 3. So, we get,

$$\eta_{d/m} = \frac{k2L12}{3}$$

So, when we are dealing with low-frequency regimes when k is small. respectively. Then in that case, the denominator, this KL, is smaller than 3, the denominator. So, overall, this quantity becomes smaller than. So, this becomes smaller than 1 in the case of low frequency. So, which means that the efficiency of a dipole is much smaller than a monopole at low to mid-frequency regions.

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