Acoustic Materials and Metamaterials
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Lecture – 27
Applications of Acoustic Metamaterials

Welcome to lecture 27 in the series of Acoustic Materials and Metamaterials. So, we are in the week 6 of our course and today we will see some Applications of Acoustic Metamaterials. So, this will be our last lecture on the general discussion on acoustic metamaterials, and from next lecture we will begin to study about membrane type metamaterials. So, let us see what are some potential applications.

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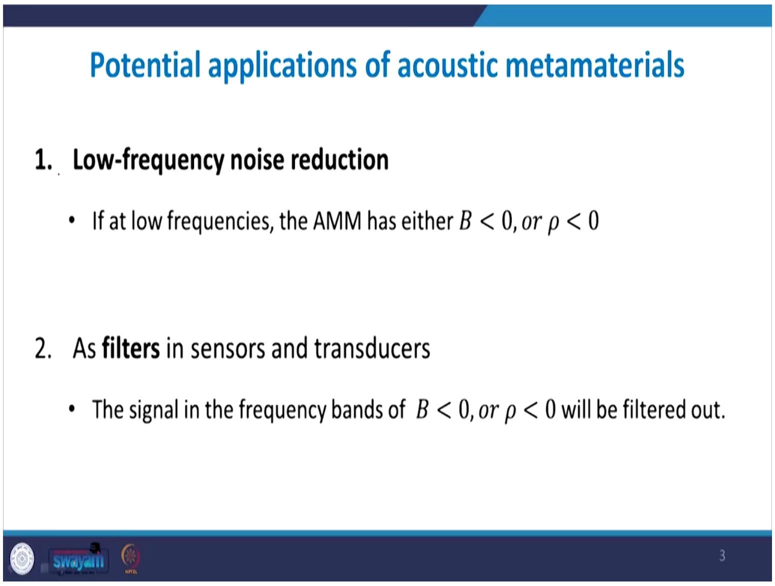

So, the potential applications of acoustic metamaterials are of course, what we began with was that the traditional materials they have limitations. So, they are not able to perform well at low frequencies.

So, the first application of metamaterial is the low frequency noise reduction. And how can they achieve this? So, if a metamaterial can be designed, so that at broad range of low frequencies, it either has a negative B or it has a negative rho. So, either a negative B or a negative rho which will mean that, the speed of sound will become imaginary; the propagation vector itself will become imaginary. So, there will be no sound propagation.

So, at whenever either of this value becomes negative, the sound propagation suddenly stops through the material. And this was discussed in the second lecture on introduction to acoustic metamaterials on how this sound propagation stops and what happens when either of this variable becomes negative. So, you can refer to the second lecture on introduction to acoustic metamaterials or the lecture number 25.

So, this is how they can achieve low frequency noise reduction, they can also be used as filters in sensors and transducers. So, what does that mean is that now we know that, at the region where there B is negative or at the region where the rho becomes negative; then the sound propagation stops the material block such kind of sound waves wherever at whatever frequency is B and rho are negative. So, at those frequency bands, these kind of signals will be filtered out. So, it can be used to as a filtering device in various such sensors and transducers, to filter out certain frequencies where B and rho will become negative.

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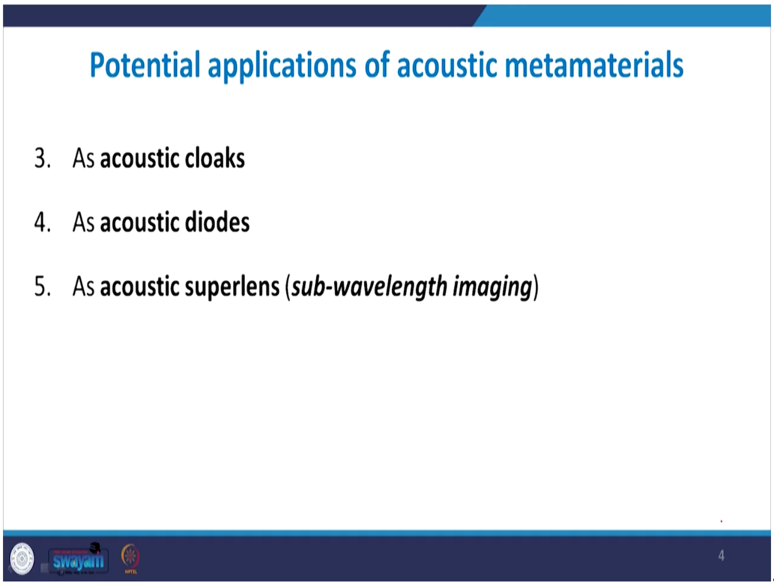

The other potential applications are used as acoustic cloaks, acoustic diodes and acoustic super lens. So, I will go through the concept of acoustic cloaking and acoustic super lens in this lecture. Acoustic diode is not within the scope of our course; but if you are interested you can obviously go and do some further reading, because this one requires more knowledge of electronics and electrics. So, let us go through what are these two specific applications which is acoustic cloak and acoustic super lens.

So, what is meant by an acoustic cloak? So, if you for example, if you have seen the movie of harry potter, he had a invisibility cloak. So, it was kind of a cover or a shawl that he any person could wear, and as soon as they wear that shawl they become invisible. So, how does that cloak work; the way that look works is that, it behaves as if the sound wave, the light wave that are hitting the material, hitting the cloak material they bend around it and they pass through.

So, there is no change in the light waves. How are we able to see somebody? Because we were able to see the light rays that are reflected from that object. And an invisibility cloak means that, it does not reflect the sound waves sorry the light waves it simply passes them through. In the same way acoustic cloak can be designed. So, it can be.

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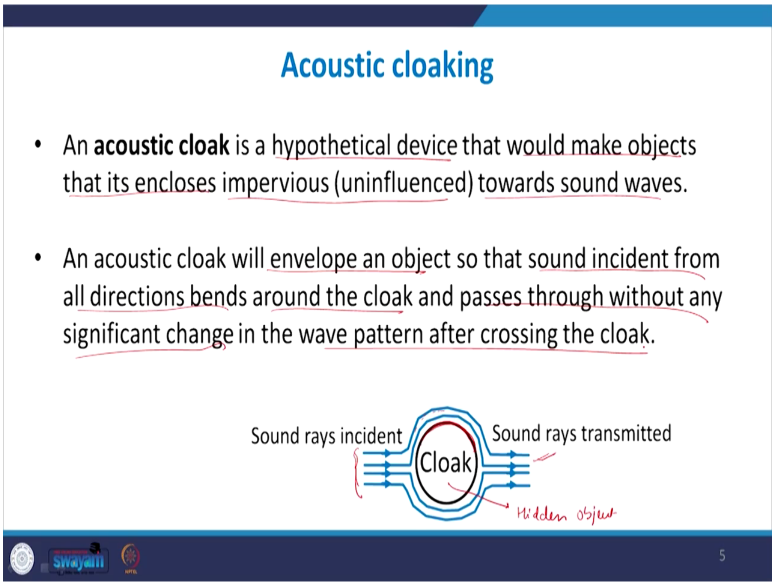

So, this means that, this is a sort of a hypothetical device which would make objects that it encloses impervious or uninfluenced towards sound wave.

So, let us say we have this cloak or this material, and inside this material we have some hidden object. So, there is some object that we want to hide, then we cover it with this cloaking material; and when the sound waves are incident on it, then accused this is a application of acoustic metamaterials. So, let us say this thing is made up of some acoustic metamaterial which manipulates the sound wave in such a way that it bends it around.

So, as a sound wave comes near the contact of this material, it bends around; lot of bending take place. So, and then it passes through on the other end uninfluenced or without any change in the pattern. So, what it looks like is that, the kind of wave pattern that was there before hitting the object is the same as what happened after hitting the object. So, the object that is placed in the path of the sound waves, it does not affect the sound waves, it simply makes them pass through.

So, this kind of pattern can also be thought of as; suppose you have a river and you have a stone in between and there water is flowing through, then the water will simply flow around the stone and then again flow. So, the stone will have no effect on flow of the water; in the same way this cloak is designed. So, what does it do is that, it will envelope in object; sound incident from all the directions will bend around the cloak, it will pass through without any significant change in the wave pattern after crossing the cloak.

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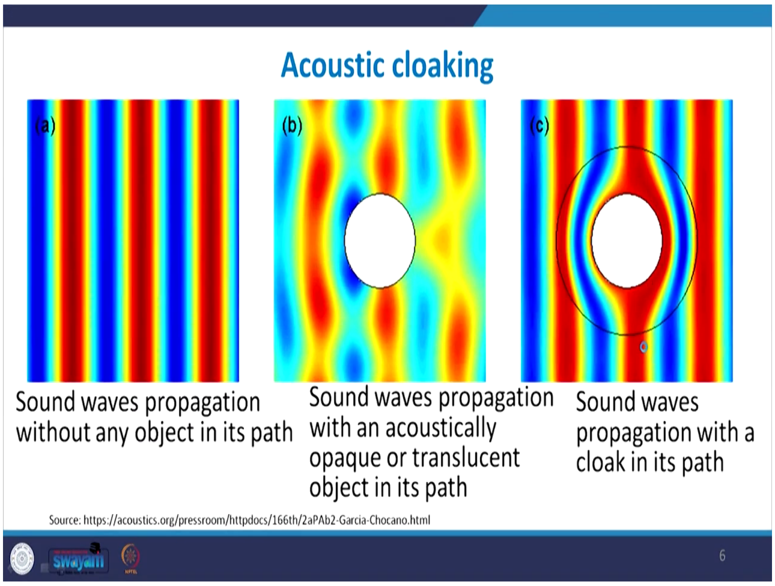

So, this is let us say this was a typical wave front in a homogeneous medium, this one.

So, as you can see the sound wave is passing through and there is no obstruction or deflection or diffraction; no scattering, no diffraction nothing is happening, it is just uniformly passing through. So, what to an observer here? So, if suppose there is an observer here, and some sound waves are incident. So, for him the way and there is some observer here. So, the way he sees the sound and the way he receives the sound it is the same. So, for them there is no object in between; but if there was some object in between and we had some emitter and some receiver here. So, what it will look like is that, there is some object in between and that is why the wave front has got distorted suddenly and it is scattering and reflections are taking place. But what does the cloak do? So, this is the pattern of wave that is being emitted. When it reaches around the region of the cloak, then some sharp bending takes place all around and then after the bending when it crosses through, it again regains the same pattern.

So, acoustic metamaterials they can be designed; because we know that they can be made to have negative refraction, they can be made to stop and block the sound waves. So, they can be made to manipulate or bend the sound waves as they want to. So, the property of the metamaterial can be so designed that, when the sound wave hits it, it keeps bending around its circumference. So, if this is the object here and the sound wave is hitting it; it bends around all over it is circumference and after bending, again it regains the original pattern. So, what it will look like is effectively this object will have no effect on the sound flow.

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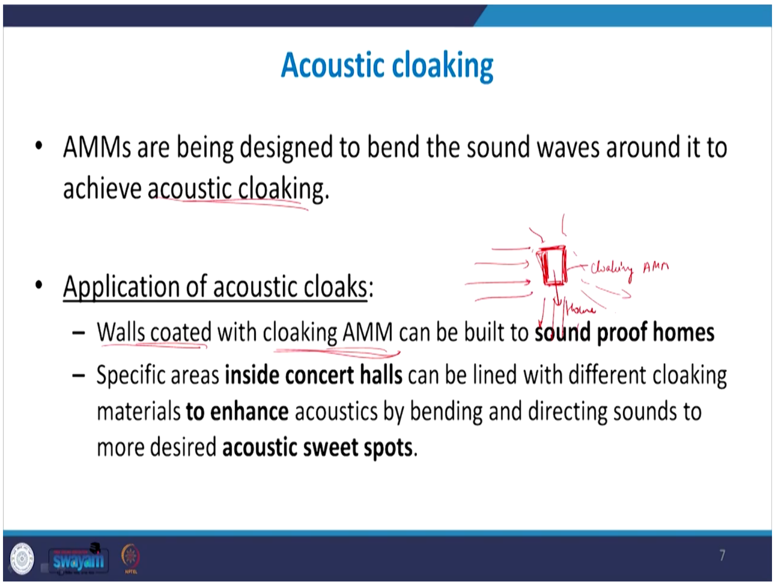

So, how can this be used? Now, we know that most of the some of the applications of this cloaking device could be that we can coat the walls of a building. So, walls can be coated with a cloaking acoustic metamaterial. So, wherever any sound from outside environment is hit on the it gets bombarded on the walls of the waves it just bends around, it never enters the house, it just bends around and passes through. So, if you coat this wall you are say sort of sound proofing your room. So, it could be done.

So, sound proofing can be done when the outside wall materials, if this is the house here and the outside is painted with some cloaks. So, this is the a cloaking acoustic metamaterial and this is the house. So, when the waves are hitting from any direction, they will just bend around and pass through without entering the material itself, without entering the home itself. So, it will become uninfluenced or unaffected by the sound waves.

In the same way this kind of material can also be used inside concert halls. So, you can have different patches of such materials placed at different locations. So, whenever a singer is singing or somebody is performing on stage and the sound waves are propagating; it can hit those patches of material, it will bend around sharply and then it can be used to focus the sound on certain sweet acoustic sweet spots.

So, let us say we have a large auditorium or a large opera house and the singer or the musician comes and performs and we have the seating area. Then the placement of such cloaking material can be done, so that when the sound, whenever the sound hits them, it is targeted towards the seating of the receiver. So, at certain positions you get very full intensity of sound and even the seats, even the listeners who are seated at the very back end. So, the front end one can always listen to the music clearly; but the what about if it is a very large auditorium or a very large opera house, then the speakers at the listeners at the very back end, they would not be able to hear the musician so well.

So, if such kind of patches are attached; then they will be able to direct and reflect the sound, so that it can be focused around the seating area of the back listeners. So, now, the front listeners can also listen to the sound properly and the performance properly; the back listener can also see to the can also listen to the performer very properly. So, acoustics sweets of speed sweets spots can be created using such materials, ok.

Lastly and most importantly, in fact this is the most important application or the most widely proposed application of cloaking acoustic metamaterial is in defence. So, now you know that, the technique of ultra-sonic object detection or sonar such kind of techniques are used to detect the objects under the sea or under the ocean.

So, using, so you use some high frequency sound waves; it is bombarded inside the ocean and wherever it hits a object, it will reflect back. And the time taking to travel back is then used to compute what is the distance between that object and the source from where the sound is being emitted. So, we have a receiver and the emitter unit together; they impinge the sound waves into the ocean and when and they and the time taken for it to come back is measured. So, whenever reflections happen and the wave they are received back the time; then gives you what is the distance travelled by these sound waves and then you can estimate what will be the approximate distance of the object that is inside a sea or ocean.

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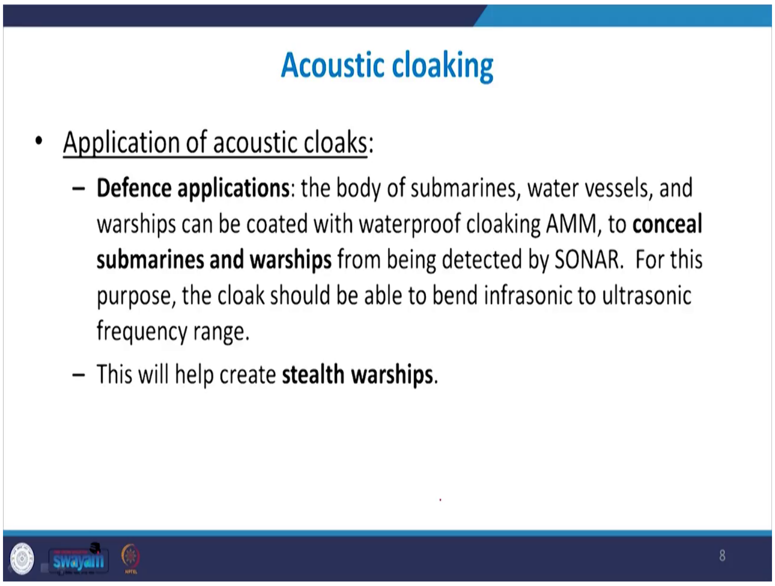

So, instead of this suppose now we have. So, this is the technique used mostly to detect submarines, water vessels, worships etcetera. So, in defence industry it is used to detect the hidden objects inside the sea. But when you concealed when you coat the body of submarines, water vessels, warships etcetera with some water proof cloaking acoustic metamaterial; then whenever the transmitted the detecting whenever the sonar signals they hit such kind of objects, then they would not be able to reflect back, they will simply bend around and pass through. So it, so because no signal will be received back; so it will look as if there is no object at all. So, it will be very easily be able to conceal submarines and warships from being detected by the technique of sonar.

And for this purpose it needs to bend these infrasonic and the ultrasonic frequency range waves. So, overall they can be used to create some stealth warships; so we can have submarines, water vessels etcetera and coat them with this kind of cloaking material. So, that when they are inside the sea, the enemy detector unit is not able to detect these kind of ships; because any sonar signal that comes to them, it just passes through and it is not reflected back. So, that is like some of the applications and the uses of acoustic cloaking technique and this is a potential application of the acoustic metamaterial.

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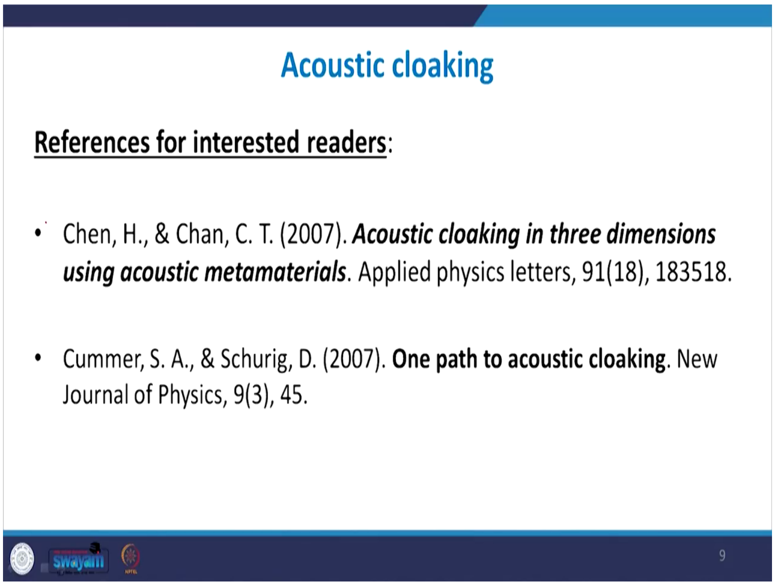

And some of the interest. So, I am given you giving you a some of the papers here, which you can take as references if you are interested to read further.

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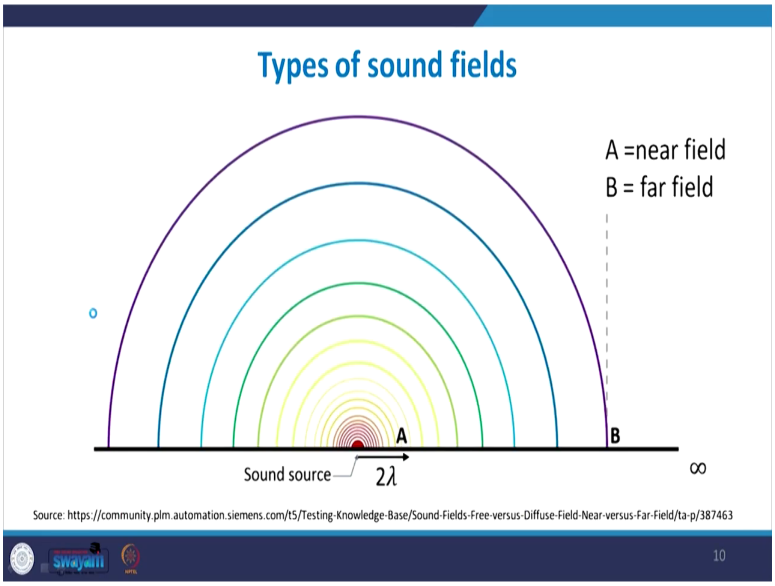

Now, let us begin with the second application that is acoustic super lens. So, before I describe what is acoustic super lensing; I have to just briefly explain to you what is the different kind of sound field, what is meant by a near field, what is meant by a far field, and what is meant by an evanescent wave. So, if this is a sound source here; then usually the sound field very close to the sound source in the order of its of the wave length of the sound being emitted. So, let us say up to a distance of 2 lambda around the sound source, the field that is existent is what is the near field. So, this A here is a near field which is approximately 2 lambdas, from 0 to 2 lambdas apart from the sound source. And all the field beyond this distance from the source then comes under far field

So, this is the near field and far field. So, sound fields are of two types.

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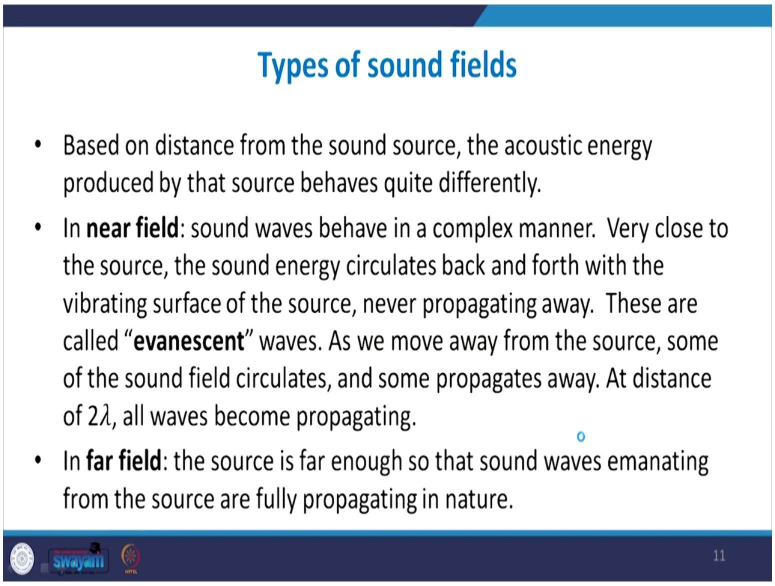

So, in the near field, so far whatever equations we studied in this course; so, we studied some equations about sound propagation through the fluid medium, the sound interactions and boundary surface, and we had some harmonic plane wave equation, we had the general linear acoustic wave equation.

So, all these equations were for the far field condition, when the sound waves they are propagating in nature. So, they are propagating in time and they are also propagating in space. So, A e to the power j omega t minus k x, this was a common expression used; but that is only valid for the far field. In the near field or very close to the source within the distance of 2 lambda, what happens is that, the sound waves they behave in a very complex manner.

So, if you see here; what happens here is that very close to the source, the sound energy it circulates back and forth with the vibrating surface of the source? So, the source is actually a vibrating surface, it is pulsating spare, or it is a vibrating tuning fork or anything like that. So, the vibrating surface creates the sound energy and this sound energy near the vibrating surface it never propagates away, it just keep circulating back and forth.

And these kind of waves that do not propagate, they rather just generate and decay are called as evanescent waves. So, very close to the source evanescent waves are developed; but as we move away from the source, then some of the sound feel it circulates and some of it propagates and after 2 lambda all of the waves become propagating in nature. So, in far field the source is far enough, so that the sound waves that are emanating from the source they are fully propagating in nature.

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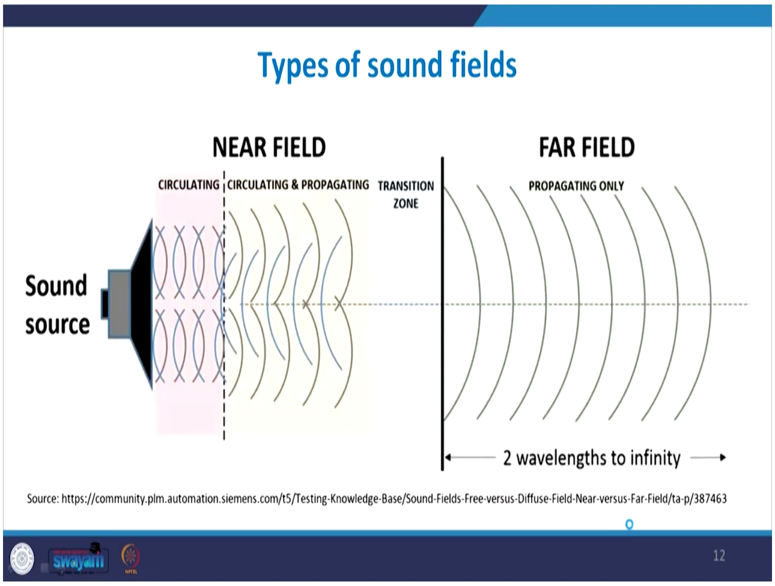

To explain this particular phenomena more clearly, let us say this diagram you can see here; we have some sound source here, and this is the near field, this entire thing is the near field.

So, within the near field of very close to the source; the sound wave is just coming back and forth, back and forth, it is never propagating away, is just circulating and dying out in the process. But after the near after the transition when it reaches the far field, most of the sound waves they become propagating in nature and they just propagate outwards in space.

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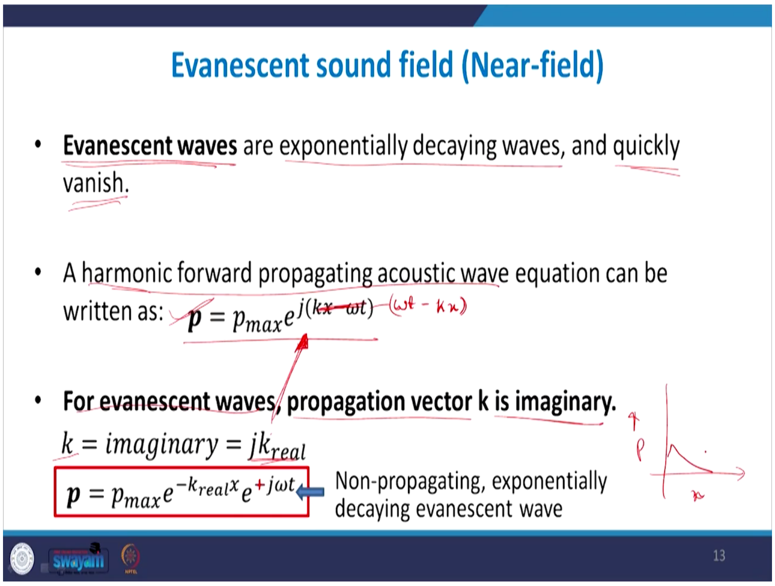

So, evanescent waves are generated in the near field and these are a typical exponentially decaying waves and they quickly vanish. So, we had studied this kind of wave in the second lecture on introduction to acoustic metamaterials, so, when I was explaining to you what happens when either B or rho becomes negative, in that case the nature of the wave. So, this is the expression for a harmonic forward propagating acoustic wave this one; but for evanescent waves the propagation vector k is imaginary. And if you refer back to the lecture number 25, so when k is imaginary, if you input this value here, k is imaginary, so it is some j times some real number. So, when you use this expression in this particular equation, so, what you end up with is some amplitude into e to the power minus k real into x into e to the power j omega t, so plus sign here.

So, this is going to be omega t minus k x, a small modification here and this is going to be plus here. So, you can refer to this derivation in the lecture 2 of acoustic metamaterials, which is the lecture number 25 overall. So, what we get is that whenever the propagation vector is imaginary; which means that, these waves they are not propagating over space. So, they are only varying sinusoidally with time, but they are decaying wave. So, they exponentially decay over space.

So, if this is x, this is p; then as soon as the wave is generated, it decays down, it is never able to reach beyond the near field. So, how does the acoustic super lens work? So, we I told you this concept of evanescent wave and near field and far field, because it is important for a discussion of acoustic super lens.

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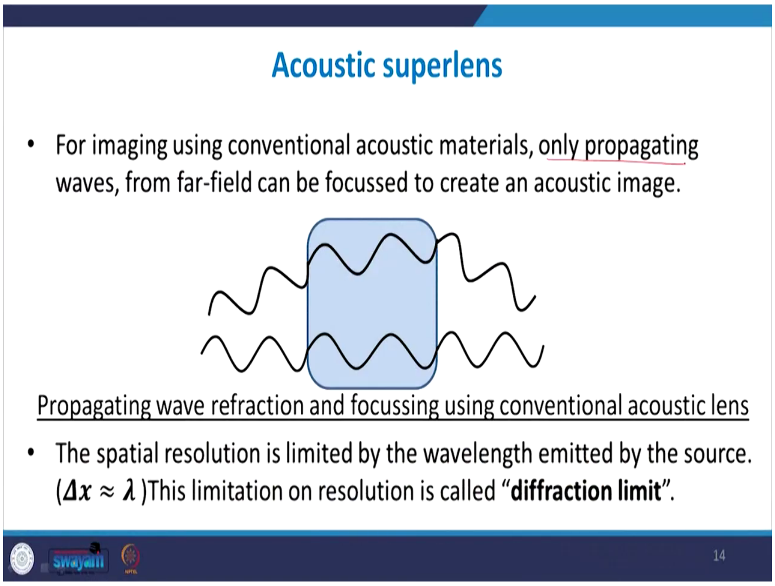

So, in a conventional acoustic material it is only able to capture the propagating waves from the far field. So, only the waves that are propagating they will be bent around. So, this is the wave front, it bends around; this is the wave front, it bends around and then finally it can be focused at certain point and an acoustic image can be obtained.

So, if we have a bending kind of a material, then it can bend these kind of generally propagating waves. And in that case the spatial resolution is limited to the wavelength; because they are only able to focus then far field waves, and far field begins with somewhere around 2 lambda. So, usually the order of their spatial resolution is lambda. So, the spatial resolution is given by lambda which is the wavelength emitted by the source. This is the minimum resolution del x equals to approximately lambda, and this limitation on the resolution is called as diffraction limit.

So, to explain it to you in simple terms; if you have a metamaterial layer sorry, if you have a simple conventional acoustic material layer and when the sound waves they hit, they will bend around, they will follow the shells law, after bending around from the other end they can converge. And when they converge, an acoustic image is formed or the sound focusing happens; a lens this is what is the principle of a lens, an acoustic lens, it is used to focus the sound waves at certain points.

But in such lenses it can only bend the propagating waves, so the waves coming out from the far field. And any information generated in the near field. So, whenever it is. So, in that case the resolution is lambda and whenever it is less than lambda; which means, this it is the information is coming out from the near field. And in that case we are not able to focus such near field waves or evanescent waves and some information is lost.

So, there is always a limitation. So, what could be the minimum spatial resolution to which these materials they can focus the sound.

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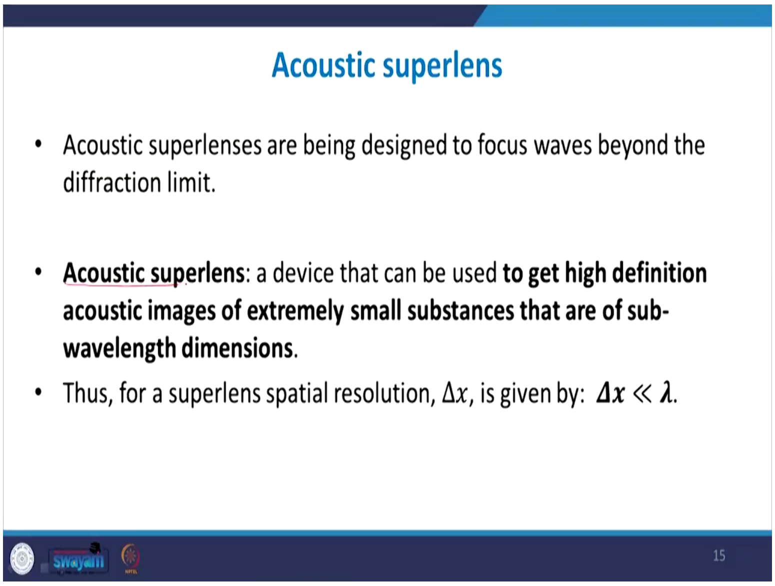

Now a super lens is what? It is a device that can be used to get high definition acoustic images of extremely small substances that are of sub wavelength dimensions. So, here for a super lens these spatial resolution will be much smaller than lambda. So, that is a lens where it can focus and the resolution can be even smaller than what is predicted by the diffraction limit.

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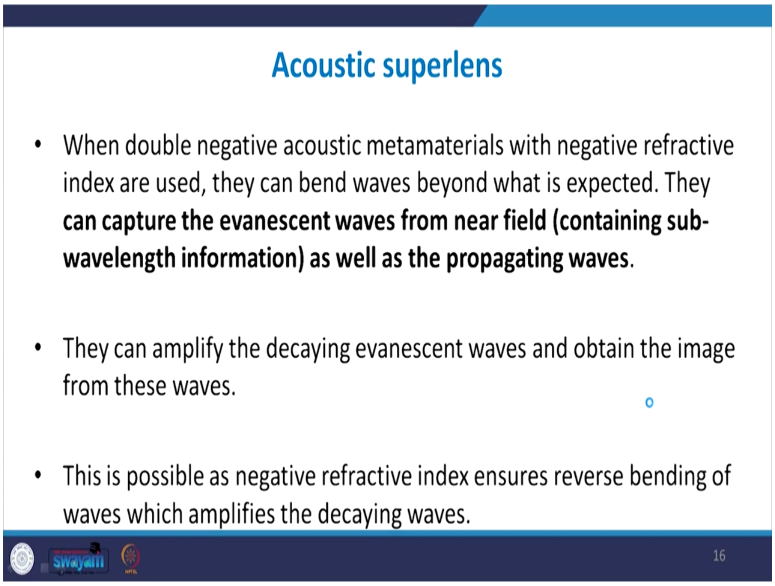

And how is this achieved?

So, when double negative acoustic metamaterials are used with negative refractive index, then they can they will be able to bend a waves very sharply unlike the conventional material. So, conventional material, suppose this is the conventional type of bending; but with a negative index material if the wave hits in this direction, it can bend very sharply. So, very sharp bending can be obtained and that is why we would be able to capture this evanescent waves which are coming from the near field. So, if you place this lens very close to the object, it can even capture the evanescent waves as well as the propagating waves.

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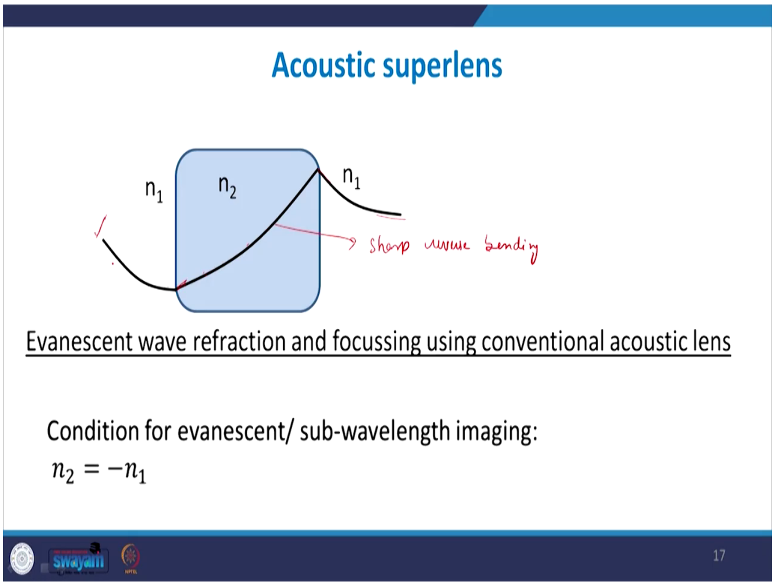

So, how are the evanescent waves captured? So, let us say this is a exponentially decaying evanescent wave; when it hits the material and then it undergoes very sharp turn reverse bending. So, there is a sharp reverse bending, a very sharp reverse bending is happening; because of that suddenly teaches high magnitude, after which it again comes back to it is decaying form, but by the time you can have a receiver here and you can capture this information.

So, overall what I want to say is that; if you have a acoustic metamaterial which has got a negative refractive index, so that will be able to bend the sound waves or turn the sound waves very sharply even in the reverse direction. So, if it can bend the sound waves very sharply in the reverse direction, it can be able to capture the exponentially decaying evanescent waves.

So, it will have a more clear, it can give you sound. So, it can be, it would be able to detect and focus the waves even with even when the source even when the resolution is less than lambda. And I will give you a numerical to explain this concept further, so that will becomes more clearer to you.

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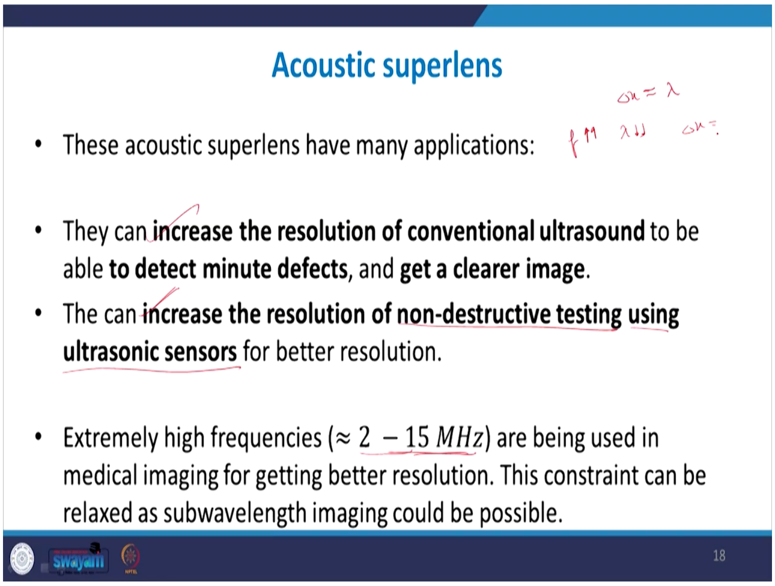

So, first of all how can these super lens be used? They can be used to increase the resolution of the conventional ultrasound techniques, which are used to detect minute defects and then it can also be used to increase the resolution of non-destructive testing techniques which use such ultrasonic sensors.

And currently for is such a ultrasonic detection of defect or for ultrasound, we use very high frequency; and what is the reason for using very high frequency somewhere from 2 to 15 megahertz, because the resolution is approximately lambda. So, if you use a very high frequency; which means the lambda value is going to be very low. So, which means the resolution will be. So, which means you will get a more clearer image; even small minute defect of the order of lambda can be detected. So, very small defects can be detective, if you use very high frequency; you want to make you want to improve the resolution, so in that case you have to increase the frequency.

But if you use low frequency waves, then in that case the resolution will resolution which is corresponding to lambda will be bigger and some of the minute effects may not be detected in that. But if you use the super lens, then even low frequency waves can be used to detect some minute defects; because in that case the resolution is not limited to lambda, the resolution can be much smaller than lambda.

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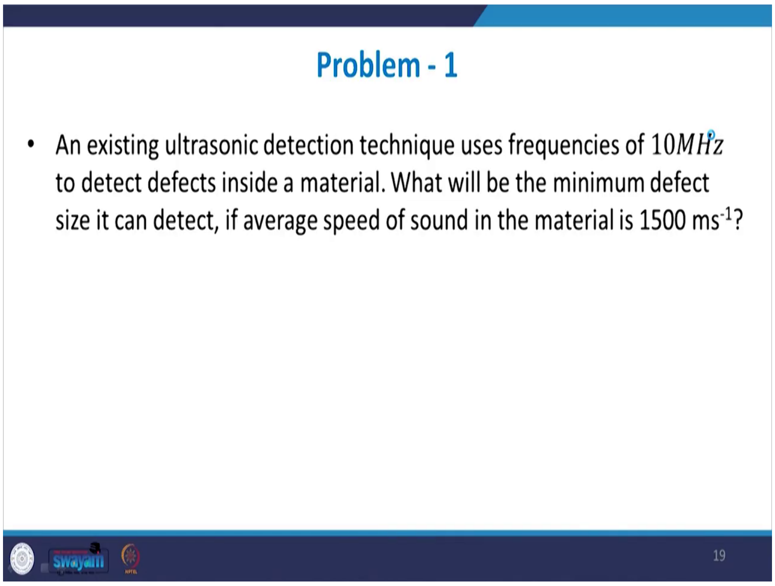

So, we will quickly solve a numerical here to see an example of this technique. So, here in this problem it is given that, an existing ultrasonic detection technique it uses frequencies of 10 megahertz to detect the it is inside a material. So, we have a material, we have an ultrasonic sensor which senses on the top of the material, and then it is able to detect it by impinging the sound of frequency 10 megahertz. What will be the minimum defect size it can detect, if average speed of the sound in the material is 1500 meters per second?

So, this is this might sound like a complicated problem, but it is very simple here.

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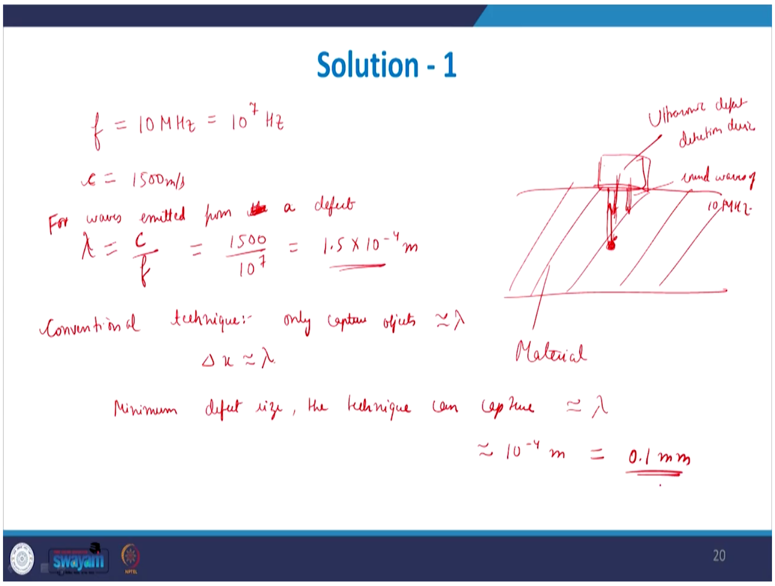

So, here what we know is that the frequency that is being bombarded by the sensor or the ultrasonic detector is 10 megahertz, which is 10 to the power 7 hertz.

And the speed of sound inside the material, so this is the material here; this is the layer of material and this is some ultrasonic defect detection device. So, what this device does is that, it does a scan and in that scan it even it sends away the sound waves of 10 megahertz frequency. And when the sound waves hit, they reflect back and then defect is detected; and the c inside this medium on material is given to be 1500 milli seconds. So, suppose the sound wave hit certain defect here and then the reflected waves goes back.

So, what will be the wave length for this corresponding wave? The wave length, so for waves emitted from a defect, so for waves being emitted from the defect; the lambda will be the c of that medium where the defect exists. So, defect exits in the material. So, c of that medium divided by the f and the frequency remains constant is independent of the medium. So, we have 1500 by 10 to the power 7 which is going to be approximately 1.5 into 10 to the power minus 4 meters. So, this is the wave length that is being emitted by the defect, once the impinging waves hit it. So, this is the reflected wave length.

And now we know that this is a conventional technique. So, in that case it will get you can only capture the objects which are of the order of lambda; because the resolution is of the order of lambda. So, the minimum defect size is it can capture, the technique can capture; capture is going to be of the order of lambda, which is going to be the order of 10 to the power minus 4 meters or approximately 0.1 millimetres.

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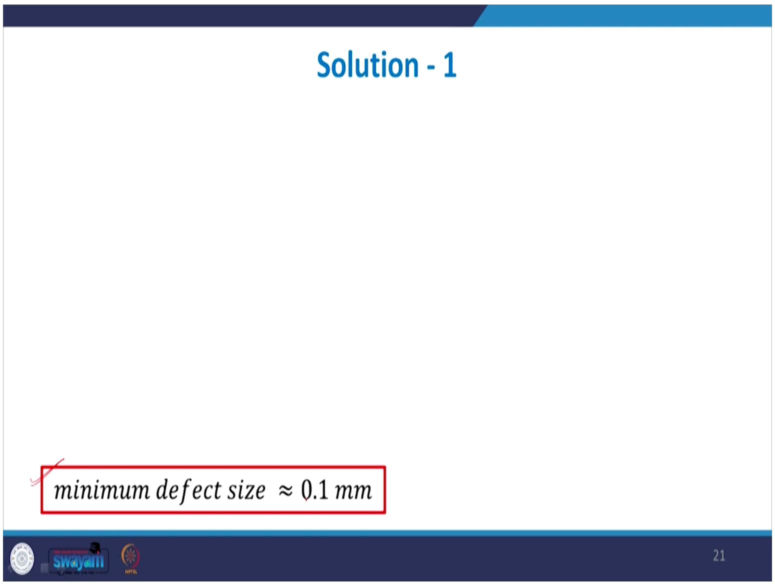

So, with this technique and with the given frequency of the ultrasound, the minimum defect size it can capture is of the order of 0.1 millimetres. So, as you see very high frequency waves are used for ultrasonic based detection, because to increase the resolution and even detect small sized defects. But if we had an acoustic metamaterial; in that case where even low frequency waves could be used, because then the spatial resolution will be of the order much smaller than lambda.

So, with this I would like to end the discussion on what are the potential applications of acoustic metamaterials. So, these are the applications that are being proposed; most of these are theoretical in nature and till now we are still waiting for some experimental verification of these ideas. So, from the next class we will begin our discussion on a particular metamaterial which is a membrane type meta material so.

Thank you.