Acoustic Materials and Metamaterials

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Lecture – 39
More on Sonic Crystals and Conclusions

Welcome to the last lecture in the series on Acoustic Materials and Metamaterials. So, in this full course we have covered a lot of topics come starting from the introduction to the concepts in acoustics, some other advanced concepts in acoustics and then proceeding with discussion on the traditional acoustic materials such as the porous sound absorbers, the barriers, enclosures, Helmholtz resonators, micro perforated panel absorbers and so on and then we finally, began with the discussion on the new engineered materials called as the metamaterials, which are now used for acoustic purposes.

And we have studied two particular metamaterials; one was the membrane type acoustic metamaterials and the second was the sonic crystals and this last week we have been discussing about the sonic crystals. So, in this last and concluding lecture of this course, I will discuss a few more things about sonic crystal.

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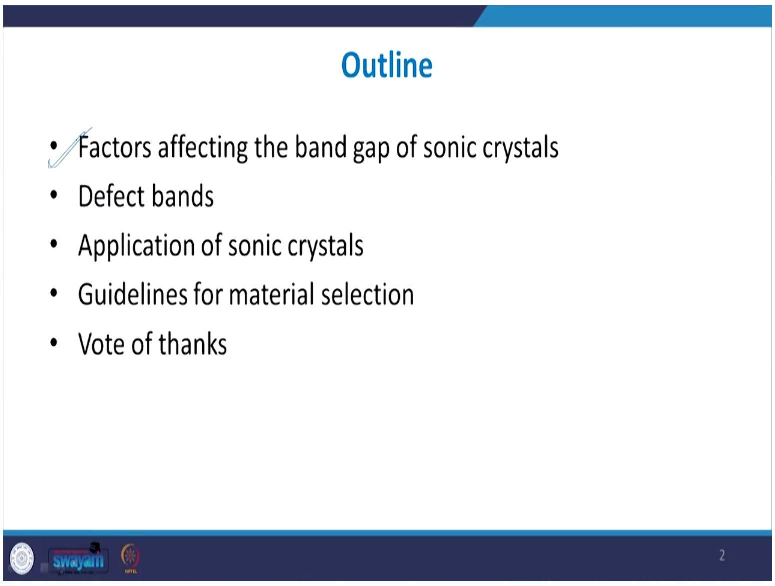

So, in particular I will start discuss about the various factors which are affecting the band gap of sonic crystals. So, how does the various factors they affect the band gap, then we will discuss some concept called defect bands and then just discussion, a brief discussion on what are the applications of sonic crystals and then I will just give you a few tips and guidelines on material selection and I will conclude my lectures with a vote of thanks.

So, what are the factors affecting the band gap of sonic crystal? So, far we have studied how does a sonic crystal operate, it uses two different types of a principle. First is the principle of the Bloch's theorem, where a periodic wave is generated inside a periodic structure and the periodicity.

The spatial periodicity or the lambda of the wave is the same as the lattice constant of that periodic structure or the length of periodicity. So, in that case what happens when such periodic waves are generated? All these waves are always quantized and there is a frequency gap between one wave; one mode to another mode.

So, always the waves they are quantized and not continuous and that is why at certain sometimes it happens that when we are measuring this wave propagation through the irreducible Brillouin zone and trying to see how the wave is propagating and, because all the frequencies are discreet for every mode, then at certain frequency gaps or bands we will get no wave propagation throughout the entire crystal or throughout the entire Brillouin zone.

So, those are called as the band gaps and the other principle was at sometimes a local resonance is created and during that time usually, it is the there is other principle is similar to the principle of a typical acoustic metamaterial. So, at certain frequencies the effective bulk modulus of the sonic scatterer, it reaches a negative value and at that suddenly when b becomes negative then the k vector it becomes imaginary, therefore, no spatial wave propagation takes place.

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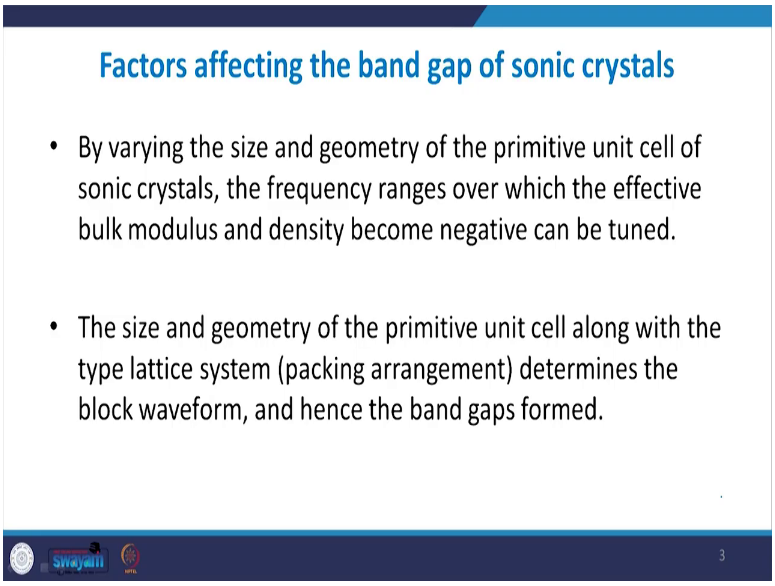

So, now what factors they affect the band gaps? So, if you vary the size and the geometry of the primitive unit cell of the sonic crystals, then the frequency range over which the effective bulk modulus and density become negative it can be tuned.

So, as you keep changing the size of the unit cell, the geometry of the unit cell and so on, you can keep changing the frequency bands over which you are getting no sound wave propagation.

So, this is just like a membrane type acoustic metamaterial, we get yet another tunable acoustic metamaterial. So, the noise control can be tuned by changing these factors, within the material. Similarly, the same factor which is the size in the geometry of the primitive unit cell along with what is the arrangement like, what is the lattice system type. They will determine what will be the block wave that is formed and hence, what will be the band gaps generated.

So, we can now list down the individual factors which, the individual factors which determine how the shape and the size of the unit cell and the lattice system changes. So, what are these factors?

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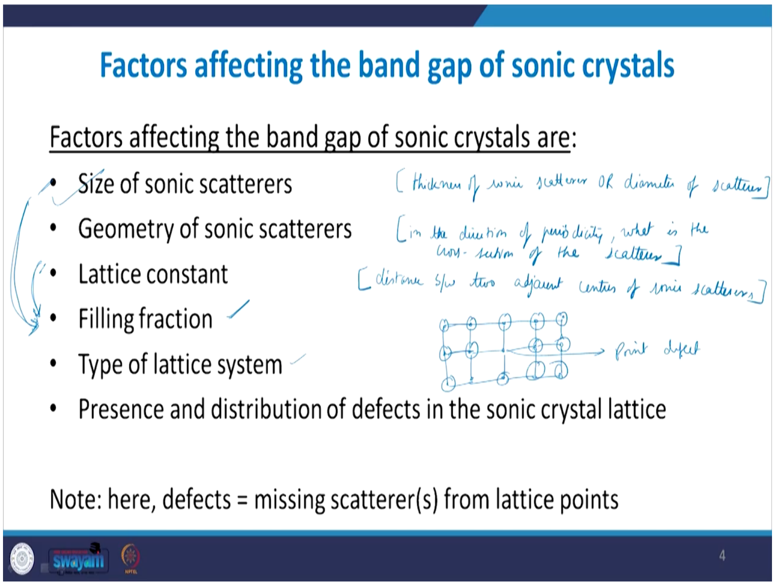

These are the size of sonic scatterers. So, this can also be the variable d let us say, it is either the thickness, the thickness of sonic scatterer or if it is a spherical scatterer, so, let us say if it is a, it is a cylinder. So, the cross section, if it is a 2 D sonic crystal and the cross section is cylindric and it is cylinder in nature in the cross section will be circular. In the same way if you have in a 3 dimension you have a spherical sonic scatterer, so in that case the diameter; so, this is the symbol or simply write it like this. So, you can either say what is the thickness or in other words what is the diameter of the scatterer that we are using. So, that will be the first variable. Then what is the geometry of the scatterer which means effectively in the direction of periodicity or in the direction of periodicity, what is the cross section like, what is the cross section of the scatterer, is it circular in nature, is it is it rectangular, is it triangular and so on.

Then it also depends upon the lattice constant. So, we know that thickness of the sonics, the diameter of the sonic scatterer is one variable, then we have the lattice constant which determines the spacing between the scatterer. So, it is the distance between two adjacent centers of the sonic scatterer. So, effectively what is the spacing between the sonic scatterer and then the filling fraction? Now if; obviously, if a, if the diameter and the lattice constant is changing.

So, if diameter is let us say denoted by a variable d and the lattice constant by the variable a, typically then if a and d change then obviously, the filling fraction will change or if the radius and the radius that is r and the lattice constant a changes then obviously, the filling fraction is going to change.

So, in that case the most important parameter is this filling fraction and these two are actually this one and this one they together determine what will be the filling fraction like. So, it changes because the filling fraction changes. Similarly, it also changes depending on the type of arrangement you use, whether you use a square packing, or hexagonal packing and so on and then it also depends; so, a new factor is that it also depends on the presence and the distribution of defects within the lattice system.

So, what do you mean by defect here? So, here in this course the defect means that let us say we have this particular lattice system, this is the lattice point and this is the lattice arrangement and so on. So, it is an infinite array like this let us say and at each lattice point we have a scatterer placed, but let us say one scatter has not been placed at one of the lattice point, then this can be called as a point defect.

So, here what you have? It means that a scatterer is missing from the lattice arrangement. So, let us say if one of so, it can also so, the band gap will also depend upon this missing scatterer. So, if some one of this scatterer is removed from the lattice arrangement, then how will the band gap be effective? We will study about this in the consecutive slides. So, these are the individual factors.

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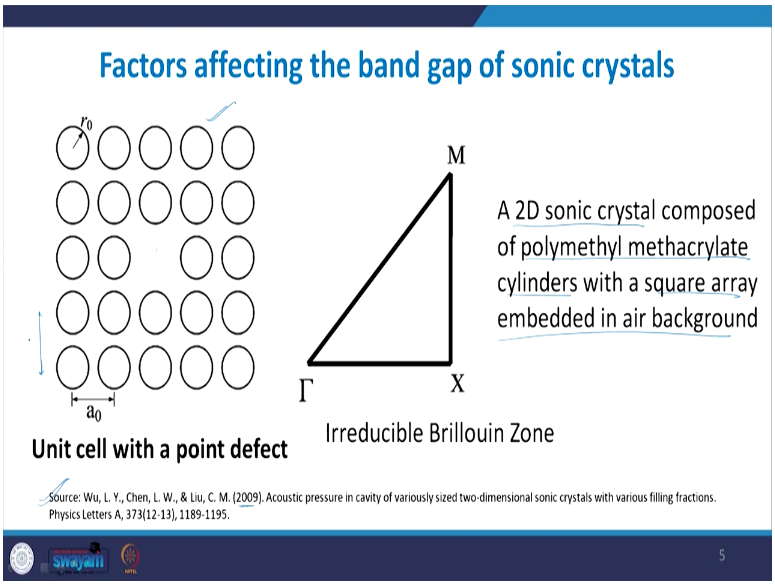

So, let us say I am going to here discuss about a paper which was by Wu. At L, in 2009, it was a pioneer pioneering work which deals with how does the band gap changed when a defect is introduced and how does the band gap change with the increase in the fillings fractions. So, two different factors have been studied here.

So, the type of unit cell is this; so; obviously, this will be repeated and infinite array can be created or a very large array can be created and there is a point effect in 5 cross 5 square lattice. So, point effect in 5 cross 5 square lattice has been given. So, this particular center or sonic scatterer is missing. Then they have measured is that they kept the r naught which is the kept the radius of the sonic scatterers and what were these sonic scatterers it is a 2 D sonic crystal which was composed of polymethyl methacrylate cylinders in a square array embedded in an air background.

So, the fluid medium was air and in the air the arrangements of these polymethyl methacrylate cylinders were made and they had a circular cross section. So, this radius of the cross section of the scatterer is r naught and a naught being the lattice constant or the distance between the centers of two adjacent scatterers. So, this is a square lattice. So, this is a naught that this means, this will also be a naught.

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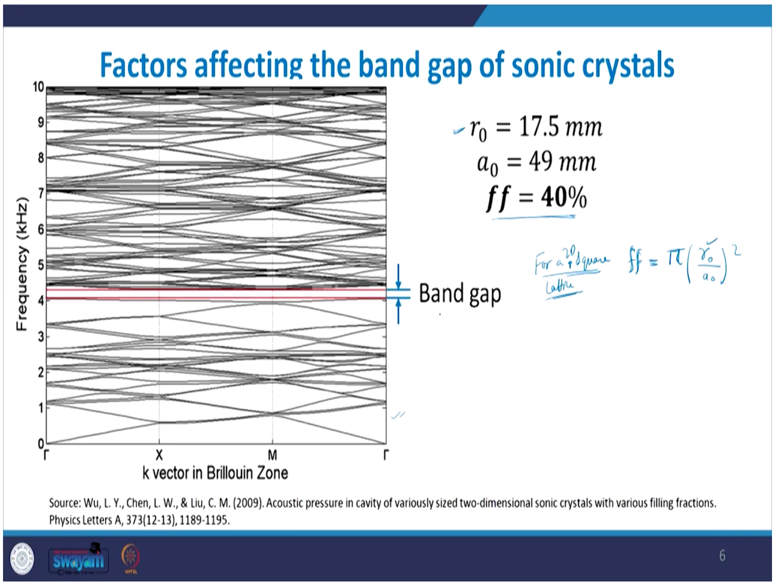

So, r naught was kept fixed and; obviously, if r naught is kept fixed the filling fraction for such lattice system is given by pi r naught by a naught square. So, we have already derived this expression in the very first lecture on sonic crystals. So, when I was discussing with you, how to what is meant by filling fraction and then of what was the expression for the filling fraction of a square lattice and a hexagonal lattice.

So, this is the expression for a square lattice; 2 D square lattice, which is pi r by a whole square. So; obviously, if r is kept constant, then a has to be varied if you want to study the effect of filling fraction. So, the conducted a series of test where r was kept constant the sonic the material of the scatterer and the material of the scatter and the background everything else was kept constant, only this a naught was varied to get different filling fractions.

So, at 40 percent filling fraction what do we get is; if you see in this particular band diagram what will be the what is the band gap? So, here this is the band over which there is no wave propagation. So, how do you obtain the band gap, you simply have to find that zone where you have no lines at all. So, the horizontal zone where there is no lines at all.

So, it will be this zone, this small zone is the band gap.

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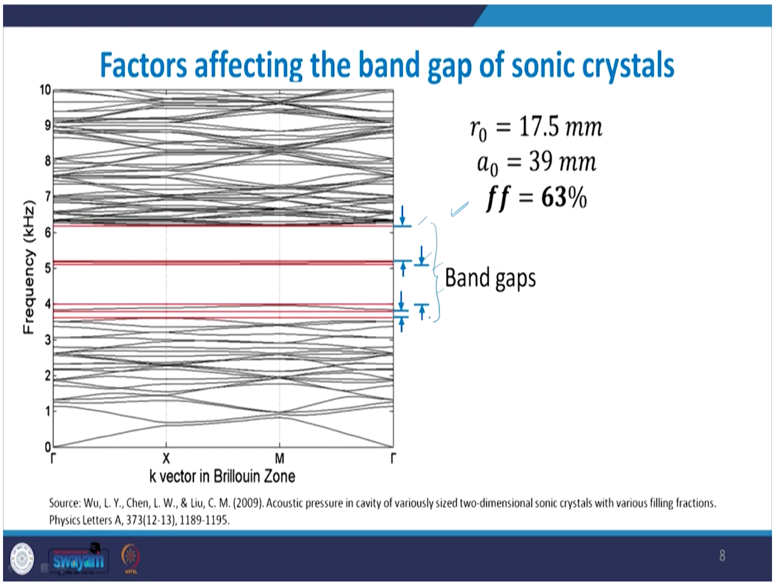

Then the same configuration was kept and only the filling fraction was now increased to 50 percent. So, for that a naught was varied, a naught was reduced. So, now, you get a much wider band gap. So, you what you see here is that you are getting two individual band gaps and there is just one line in between the two band gaps.

Similarly, when you further increase the filling fraction, you get even wider band gap here and another band gap here and a third one and just between all these wide band gaps, you only have one single line. So, this was a peculiar observation and once, they explored it further they found was that this single line which is end which is coming in between these wide band gaps is due to the point effect.

If there was no point effect you will have this entire band gap will be together. So, you will get this full band gap here, when there was no point effect. Similarly, in case of no point effect you will get this entire band gap the line is coming only because of the point effect that is what they have found over here as well.

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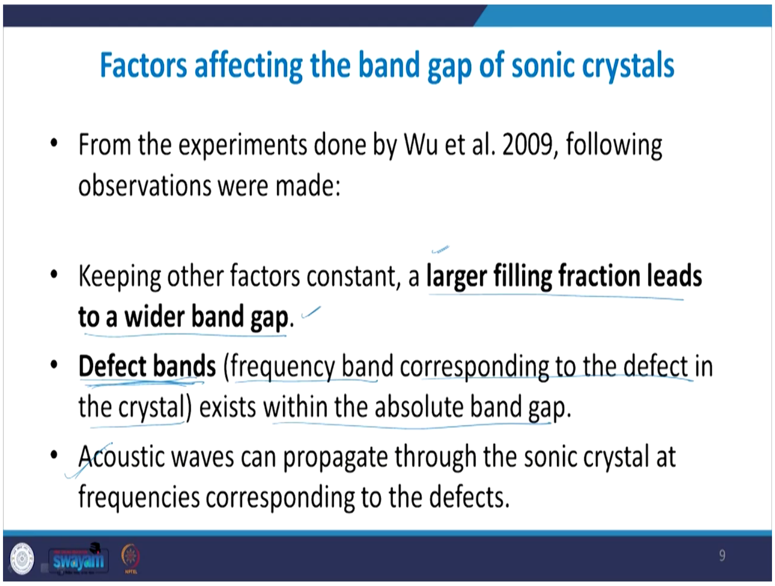

So, the various observations made in conclusions made from the work was that, if you keep all the other factors constant and you vary the filling fraction then a larger filling fraction leads to a wider band gap.

So, usually the band gap occurs around the same region. So, as you can see it is occurring around the same region typically, around the same region it is starting from the same regions. So, somewhere between 3500 to, so somewhere between 3000 hertz to 5000 hertz within that same zone, we are getting the band gap. So, the frequency and the only difference is that from narrow it is getting wider.

So, you getting a much wider band and then the single lines that are obtain in between which was due to the defect was called as a defect bands. So, these are the frequency bands, which correspond to the defect in the crystals. So, as we saw here in a 5 cross 5 crystal one lattice point was missing or one scatterer was missing that was creating a defect and therefore, we get one single frequency line, which is a defect band, which exists within the absolute band gap and, because of this which means that the acoustic waves will propagate through these defect bands.

So, sort of the, it is bifurcating the absolute band gap. Now, the frequency of this defect band is also called as the resonant frequency. So, the acoustic waves should be localized.

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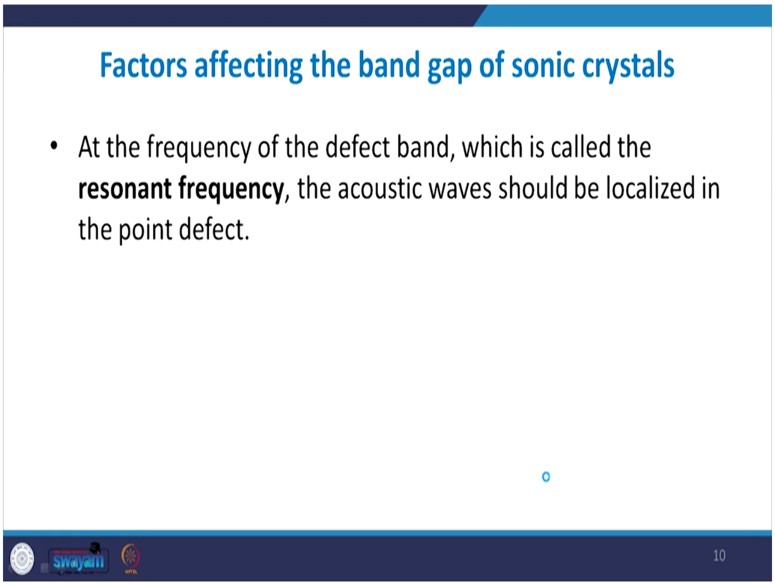

So, what happens is that it has also been found that when the defect occurs so a simulation study was donel a finite element study was done to find out what is the pressure field distribution in this particular type of sonic crystal array.

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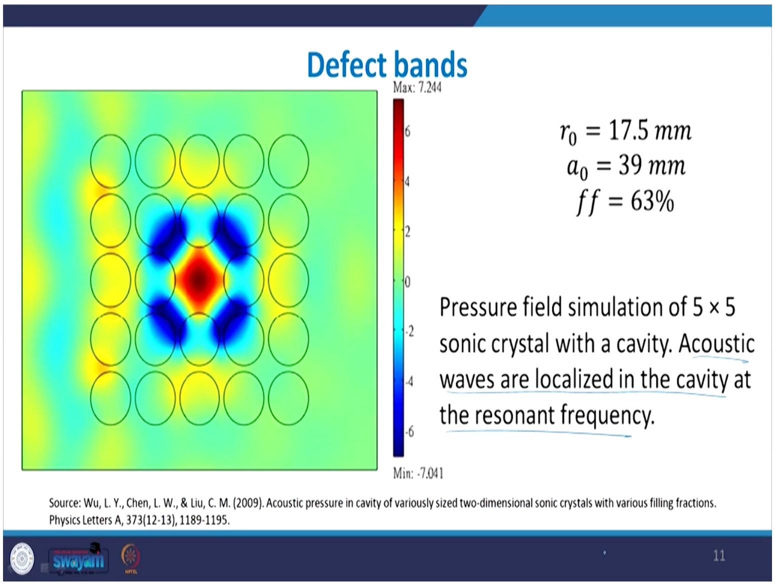

So, here as you see the same sonic crystal array is their 5 cross 5 and appoint effect at the center. So, the wave it was simulate and what you find is that when the wave front is incident and passes through this structure then some localized waves are created around the point defect. So, the acoustic waves they are localized in the cavity or at the point of point defects.

So, whenever there is a small gap a point defect or a cavity then the waves get localized which is called as the phenomenon of local resonance. So, which means that compared to the local waves compared to the other wave fronts inside the crystal this particular wave will have a much higher pressure. So, suddenly as a wave front is passing through let us say it is passing through in this direction and going outside in the periodic structure suddenly at a certain point the pressure will increase it will be sort of a local resonance created at this particular cavity.

And that is why the frequency which is corresponding to this defect band is the resonance frequency, because it is that frequency where suddenly a resonance is happening and some waves are getting localized we get high pressure waves near about at the at this point defects; however, it is not propagate through outside.

So, it is not affect the overall noise control, but what it means is that it will bifurcate the overall band gap. So, this is called as the resonance frequency. So, let us see here, what is the resonance frequency for this one?

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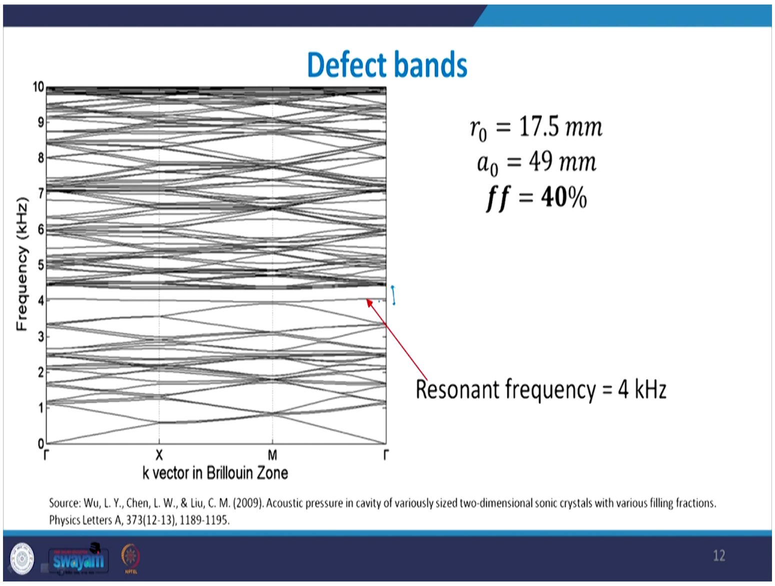

So, you see this becomes the resonance frequency. So, if this was the overall this would have been the overall absolute band, a small line that is in coming in between the absolute band corresponds to the resonance frequency or the frequency at which the defect the pressure waves are localizing in the defects.

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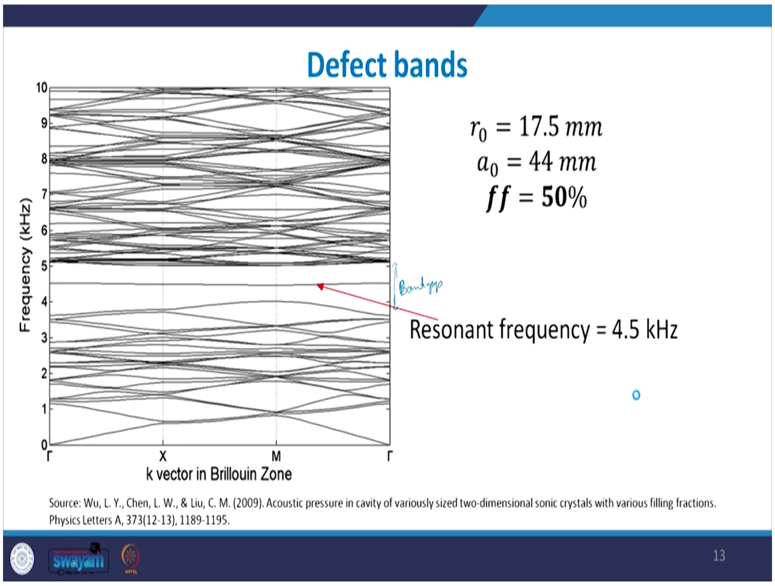

Similarly, here this was the absolute band and within this absolute band gap, you getting a single frequency here. So, this becomes the resonance frequency. So, here the resonance frequency was around 4 kilo hertz, here it is around 4.5 kilo hertz. So, this is just an average value the resonant frequencies changing slightly over the k vector.

Similarly, here you have one resonant frequency here and then there is another band. So, you get a second resonance frequency somewhere around here.

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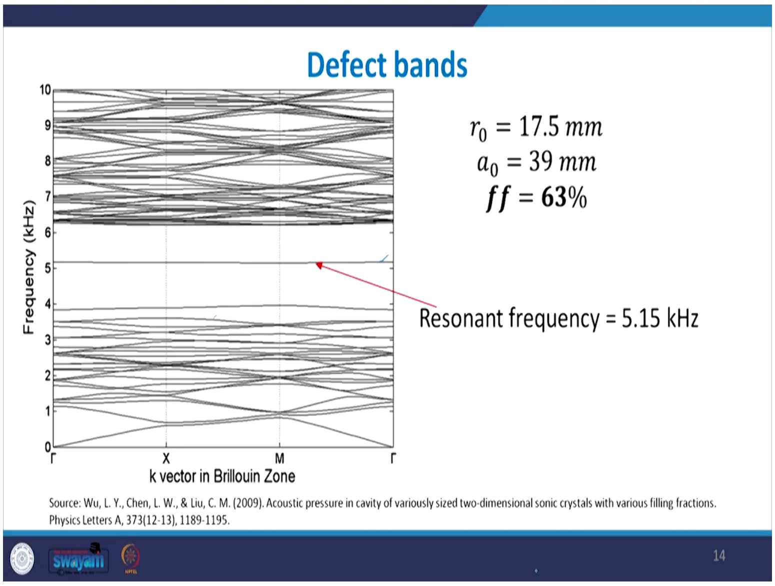

But here the second resonance frequency has not been taken into account, because it was found that the overall effect of this on the pressure wave front was minimal or negligible. So, it was only this particular resonance frequency that is effecting the wave form in the localized acoustic waves.

So, these are the three resident frequencies for the three different filling fraction. So, how do you find the resonance frequency from a band gap structure have a look at the band gap structure and you will observe some anomaly. Let us see you will observe that you have got a wide band gap and suddenly within that wide band gap you are getting only a single frequency line of wave propagation.

So, that single frequency line of wave propagation corresponds to the resonant frequency due to the defect ok.

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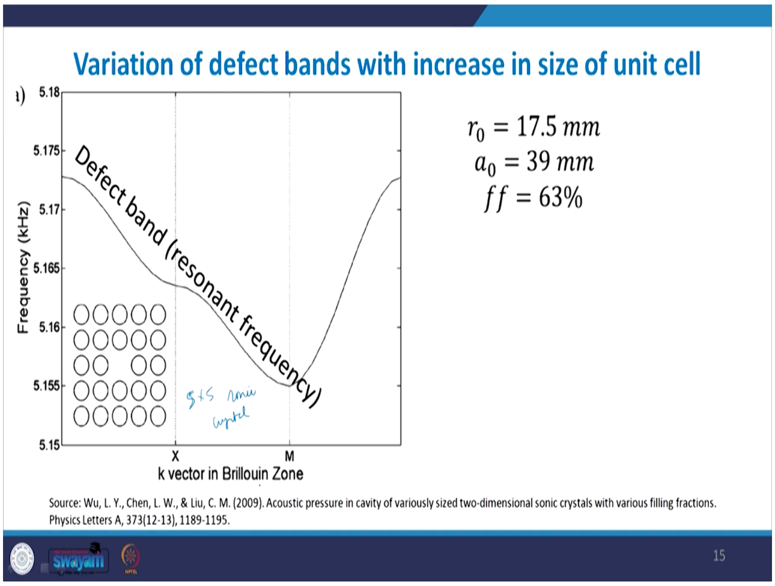

So, one more study was done to find how do these defect bands of frequency the resonant frequencies the change with increase in the size of the unit cell

So, the same point effect is there, this is the 5 cross 5 crystal. So, this is the variation of the defect band or resonant frequency; so, a large scale study. So, here the scale size has been increased. Now, when you inflow this was a 5 cross 5 crystal.

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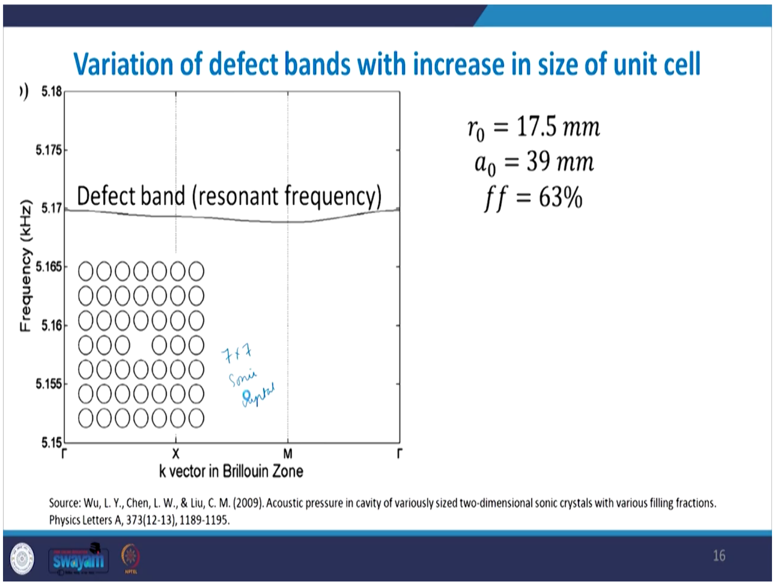

Now, here you have a 7 cross 7 sonic crystal array and you have a point defect at the center, then the frequency at which you are getting the defect band is almost the same, it is just some point variations, but it has become more stabilized. Now, the variation is not that much.

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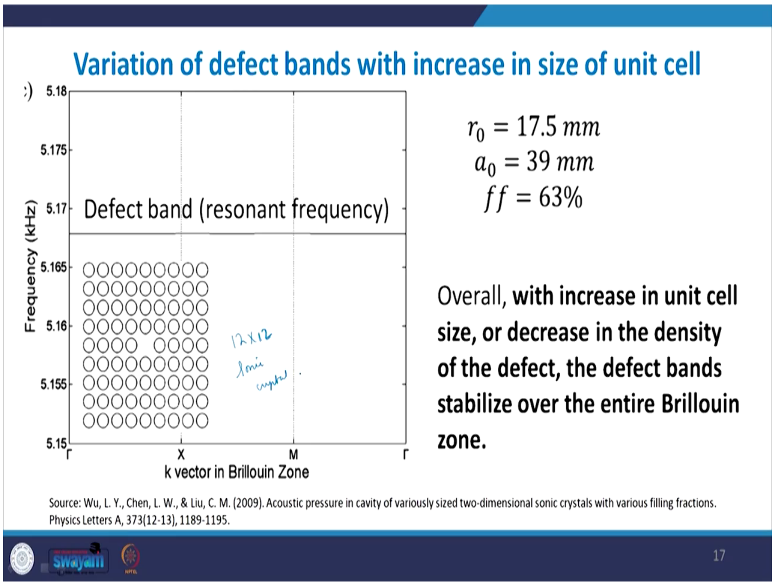

In the same way as you increase it from 7 cross 7 the 12 cross 7 12 cross 12 sonic crystal. Again, the value where the frequencies obtained or the resonant frequencies obtained is not has not changed much.

So, here the average was approximately around 5.17 let us say, here it was around 5.17 here, it was around 5.168 or something which is close to 5.17. So, the resonant frequency is the same. So, the effect is that as you increase the size of the unit cell which means that the overall density of this point effect is decreasing in this crystal array.

So, in that case the defect bands they are stabilizing over the entire Brillouin zone. So, you getting us more and more stable and horizontal frequency line as you plot the band gap structure. So, let us say you if you given a band gap structure and you have a wide band and then you have some frequency line in between that band gap.

So, that will correspond to the resonant frequency, but you can see that the frequency line will have some small amount of fluctuations which means that the size of the array is small and the point effect for as compared to the point effect and for the same point effect, if the size of the array is increased, let us say from 5 cross 5 become to 12 cross 12 or to 10 cross 10 and so on, then that same frequency line the fluctuations are going to become less and less and the and in the band gap that particular resonant frequency will become more and more horizontal in nature.

So, you get a more horizontal type of frequency line in the band gap diagram, in the band diagram.

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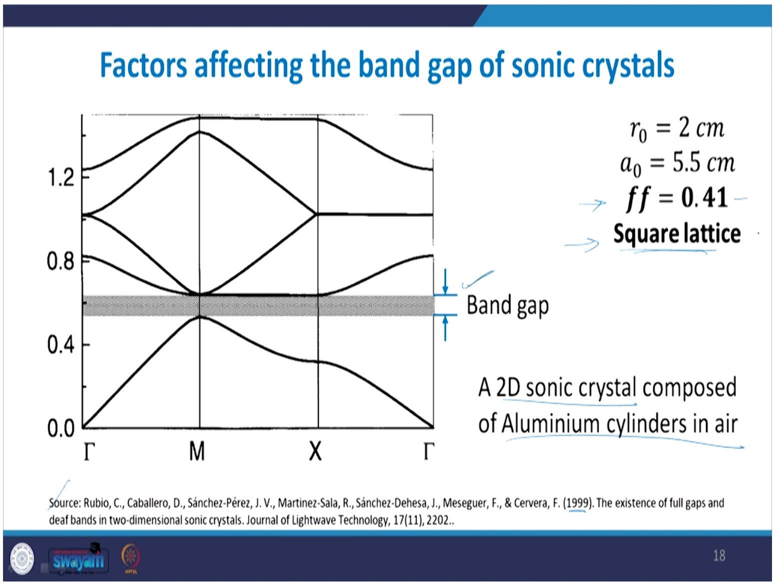

Similar study was also conducted by Rubio Et Al, 1999. So, here what they did was they studied about filling fractions and the lattice arrangement. So, here for a filling faction of 0.41 and for a square lattice, 2 D square lattice and the material was the same. It was 2 D sonic crystals composed of aluminum cylinders in air.

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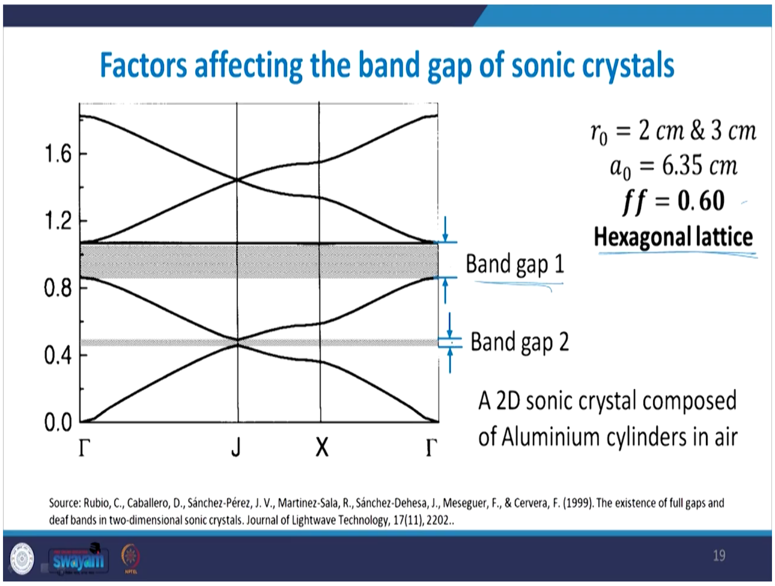

So, we have this is the kind of band gap for this filling fraction and square lattice and when you increase the filling fraction; obviously, the band gaps become wider the same pattern as observed in the previous paper, but as you also change the square, the lattice form from square to hexagonal so, you are getting another band gap. So, you are getting two different band gaps.

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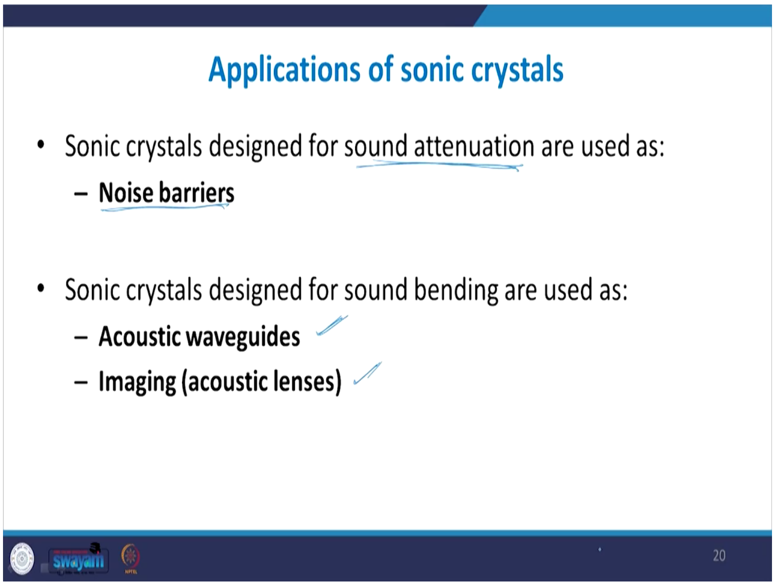

So, now that we have studied about the various effects then what are the applications of sonic crystals? They are very similar to the application of other acoustic metamaterials first of all they are used for sound attenuation. So, two different aspects where they are used, first for attenuating of sounds were stopping the sound wave propagation and therefore, they used as noise barrier especially, outside.

For example, an outside sculpture or an outside array of trees created between the highway and the residential areas, you can have an array of trees in a sonic crystal type arrangement and all of that is acting as a noise barrier to prevent the sound wave propagation.

Similarly, you can also have sound results specifically for the purpose of bending the sound waves and there you get two important application one is the acoustic wave guides. So, what do you mean by acoustic wave guide is that it is a structure which is sort of guiding the waves through a particular path.

So, the waves so, here the bending will be such that the wave some guided along a particular path and from point a to b they reach without much attenuation. So, this is more like guiding and then for imaging purposes. So, it is same as the acoustic lens and we had already discussed the concept of acoustic lens and how does the acoustic lens work. If you have a layer of acoustic metamaterial which can which has a very which has a negative refractive index.

So, which can bend the sound waves very sharply then a sharp image can be obtained both from the near field and the far field and that same concept applies here. So, the details of this acoustic imaging or the use of acoustic super lens is already been the concept of that has already been discussed, when I was discussing about the acoustic metamaterials in general before coming to the membrane type of acoustic metamaterials.

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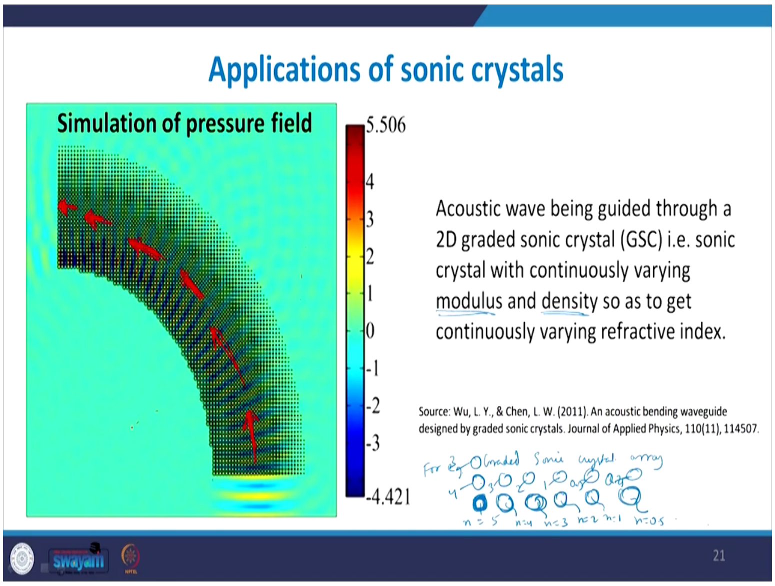

So, I will just show you the case of acoustic wave guide. So, here you have an acoustic wave guide. So, here this these are the individual crystals and the way this has been done by the author is that he had, our typical sonic crystal arrangement and that was in this form and here you know that from the analogy of the electrical field into the electromagnetic field into the acoustic field. The refractive index will depend upon the important parameters like the bulk modulus and the density.

So, once you change the bulk modules and the density you can manipulate the refractive index. So, here the refractive index is continuously changing throughout. So, this is called as a functional degraded sort of sonic crystals where you have so, let us say suppose you had an array where this one had say let us say, I am just giving an example a very rough brief example of graded sonic crystal array.

So, let us say one there was this is one scatterer with the refractive index of let us say 5, then you have something with a refractive index of 4, then you have another one with a refractive index of 3, 2, 1 and then 0.5 and so on and similarly so, this is just in 1 D and the same grading can be done in 2 D. So, when you go forward here, you will again have 4, 3 and so on and this from this 4, this will come out to be 3, this will come out to be 2 1, 0.5 0.25 and so on.

So, here the so, what it means is that the overall refractive index it is varying as a linear function along all the directions of periodicity. So, if it is a 1 D crystal, it will be along one direction; if it is a 2 D arrangement the along both the horizontal and the vertical directions.

The two directions of periodicity the refractive index will be varying linearly or it will change continuously in the two directions.

So, that is what is called as a graded kind of sonic crystal. So, the kind of arrangement that the author was studying is that they have a arrangement of a sonic crystals and here, the refractive index, because it depends on the bulk modulus and the density. So, the bulk modulus and the density was varied so as to change the refractive index with the change in the location of the crystals.

So, it was continuously changing throughout the location. So, and the a simulation study had been done and the pressure field has been sort of simulated. So, what it has seen is that when a wave front is incident then most of the wave front goes guided through the sonic crystal and it reaches. So, it follows this path. So, if I will show you this in different colors.

So, this is the path that the wave front is taking along the crystal and finally, following this crystal. So, this is sort of like how you have a hosepipe? You put the hosepipe on a tap and then you have a bucket somewhere at point b we and they are following a very irregular path.

So, you can have a hosepipe attach it to the tap, open the tap and the other end of the tap as and at the under the hosepipe you can have a bucket.

So, here the hosepipe is guiding the wave, it is guiding the water flow from the tap through the different path of the hosepipe and to the bucket in the same way. This is sort of like a acoustic pipe which is very wave front is incident, it will be guided along the particular sonic crystals and reach from point a to b and loss will be very less.

So, it is acting like a typical hosepipe that is used to guide the water. Now, we have a sonic crystal guiding the waves.

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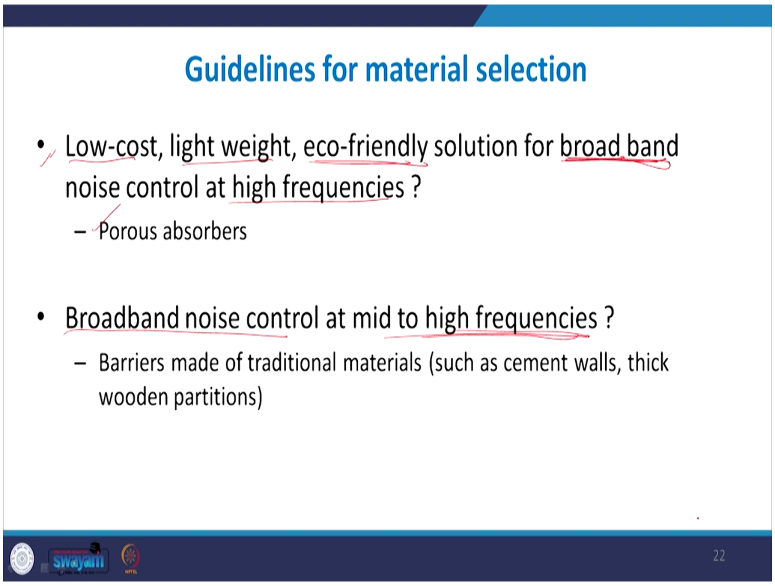

So, these were the various applications. So, I will quickly come to some of the guidelines form material selection. So, now, we have covered a lot of materials and it is difficult to give very huge list of guidelines. So, I will just give you a keep I will just pose a key questions and try to answer them so that you get a hunch of how do you select a particular material.

So, let us say the first case is where you have to select a low cost lightweight eco friendly solution for a broadband noise control at high frequencies. So, when you hear this you will see the word ok.

So, you first of fall use want to see what is the frequency range of operation. So, here you have a broad band high frequency range and what are the materials that, almost all materials work well at high frequencies and you use advanced materials only when you need some specific application, because it is usually they are not very readily constructed and they are not very readily available.

So, when you have a general high frequency application, it is better and there is no low frequency demand, it is much easier to go for a traditional material and you need a low cost lightweight and ecofriendly solution. So, once you come with this what eco friendly, then you would recall that the porous sound absorbers.

They can be made with natural materials like for example, you can have a jute fiber composite or you can have something made with cotton something made with coconut coir and so on and all of them are able to act as porous sound, porous fibers medium and the sound wave is sort of controlled at high frequencies at a broadband range.

So, a porous absorber could be a solution here, let us say you have another case where you have to do a broadband noise control and mid to high frequencies. So, again it is a broad band noise control mid to high frequencies and there is no other constraint like a constraint of weight of the material or the cost of the material and so on.

So, again for a general purpose solution you can begin with a traditional material and any traditional barrier material can do the job here, because it is again not a low frequency so; obviously, you can use a sonic crystal; obviously, you can use some other advanced micro perforated you can use a sonic crystal or you can use membrane type things actually, you cannot there specifically for the low frequency.

So, for typical mid to high frequencies, so for high frequency purposes, it is just a general, it is a general tradition to use conventional materials go for them. Now, we come to the low frequency application.

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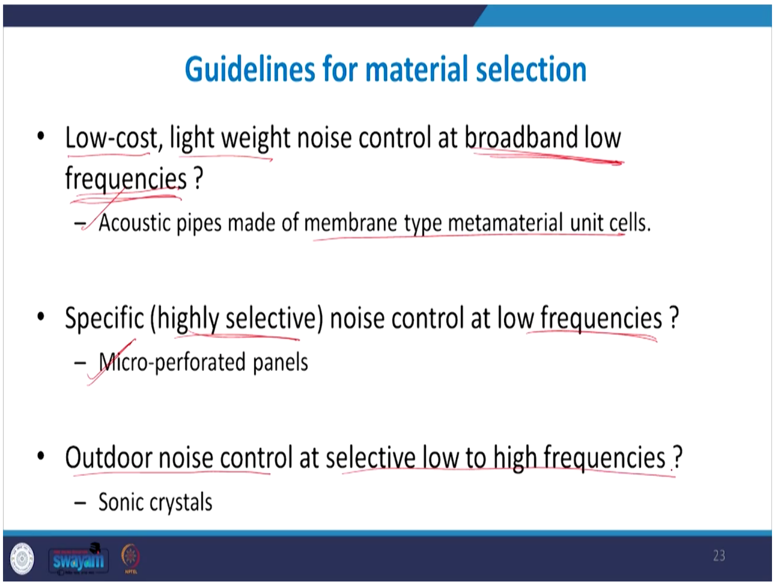

So, let us say now you need again a low cost solution lightweight, but for broadband low frequencies. So, all of this was were high frequencies and you directly went with the traditional materials like the absorbers or the barriers.

Now, for broadband low frequencies, the if you think about it one of the only few material that will specify that is going to satisfy this condition is the membrane type acoustic metamaterial, because all the other materials which are designed to work at low frequencies like the

Helmholtz resonator or the micro perforated panels even the sonic crystals. They have, they do not have a very broad band gap.

It is the membrane type acoustic metamaterial which has a broad band range over which the sound is attenuated which is from 0 to omega naught where omega naught is the natural frequency of the unit cell.

So, when you hear this thing broadband low frequency which means you can use an acoustic transmission line or pipe which is made up of membrane type metamaterials as a unit cell then let us say you want something for a very selective purpose of very specific noise control at low frequency. So, now, the desire is not to cut down all the frequencies at low at all the low frequencies let us say you go you have a waveform and only you want to cut down a certain transformer noise or a certain signal.

Only a certain signal at a particular frequency you want to cut down that is the only purpose, you do not want to cut down all the frequencies. So, for that selective operation where only some discrete frequencies need to be cut down, you remember. If you remember very correctly, we had micro perforated panels. So, both helmholtz resonator panel absorbers and micro perforated panels, they all have selective absorption, because they only absorb at their own resonance frequency when there is a acoustic coupling, but because out of the three cases micro perforated panel gives the maximum absorption magnitude.

So, that will be a better choice for a selective high a selective low frequency absorption or a very discreet and point low frequency absorption. Now, similarly you want something for a outside noise control at a selective low to high frequencies, then sonic crystals could be used.

They are mostly used for, because incase of sonic crystals are main limitation is the sizing. So, they usually used as outside barriers and sonic crystals can be used.

So, I have covered the course here and I just give you a few tips on how the various materials can be selected depending on what is the application and what is the constraint like such as the cost or the weight factor or the type of frequency range you want to cut down.

So, accordingly you can go for different acoustic materials. So, with this I would like to conclude my lecture and when I conclude my lecture, I would like to thank a few people who have helped me in this particular lecture series.

So, first of all I would like to thank IIT Rookee and then MOOC and NPTEL they have given me the opportunity and an appropriate platform where I can create and conduct the very first series and acoustic materials and metamaterials. I would, I am also grateful to my team here. So, my team constitutes for us in particular its Sharath from E learning center at IIT Roorkee and my research assistant Vikranth Dutt, who is the Mtech student at IIT Roorkee, they have helped me with the recordings of the lectures, compiling of the lectures as well as with putting up and managing the online portal.

So, I would like to thank my team and I would also like to thank my postdoctoral supervisor professor A R Mohanty from IIT Kharagpur, it was under his guidance where I learned a lot about acoustics and acoustic materials and he has been a guiding force in my life.

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Thank you.