**NOISE CONTROL IN MECHANICAL SYSTEMS**

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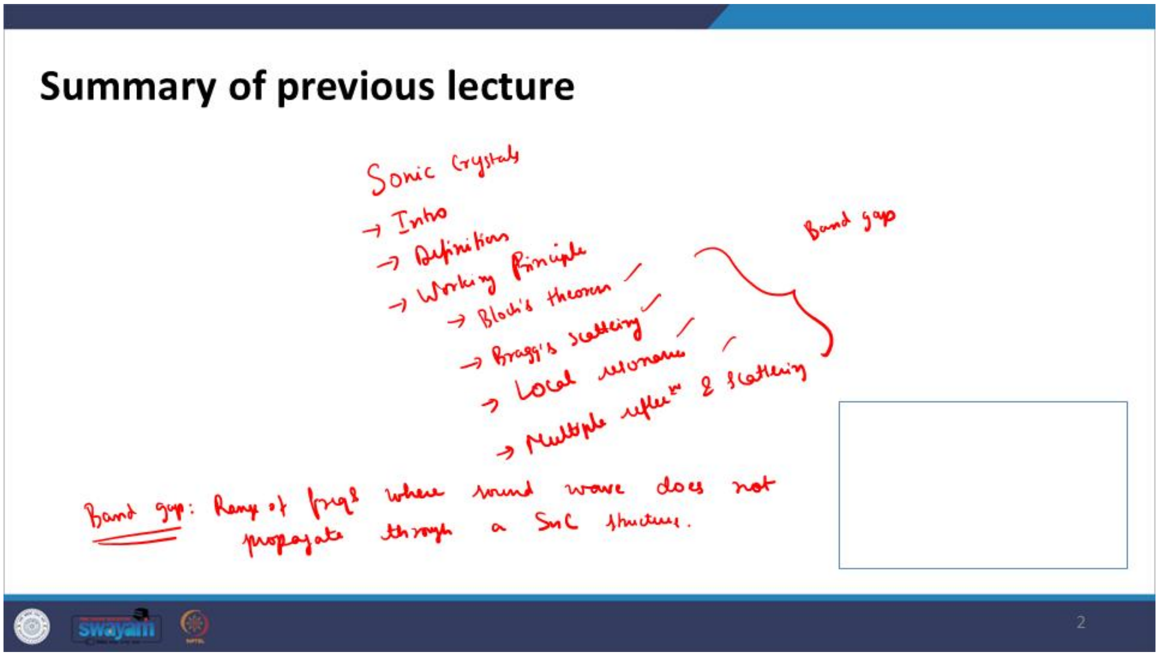
**Week:11**

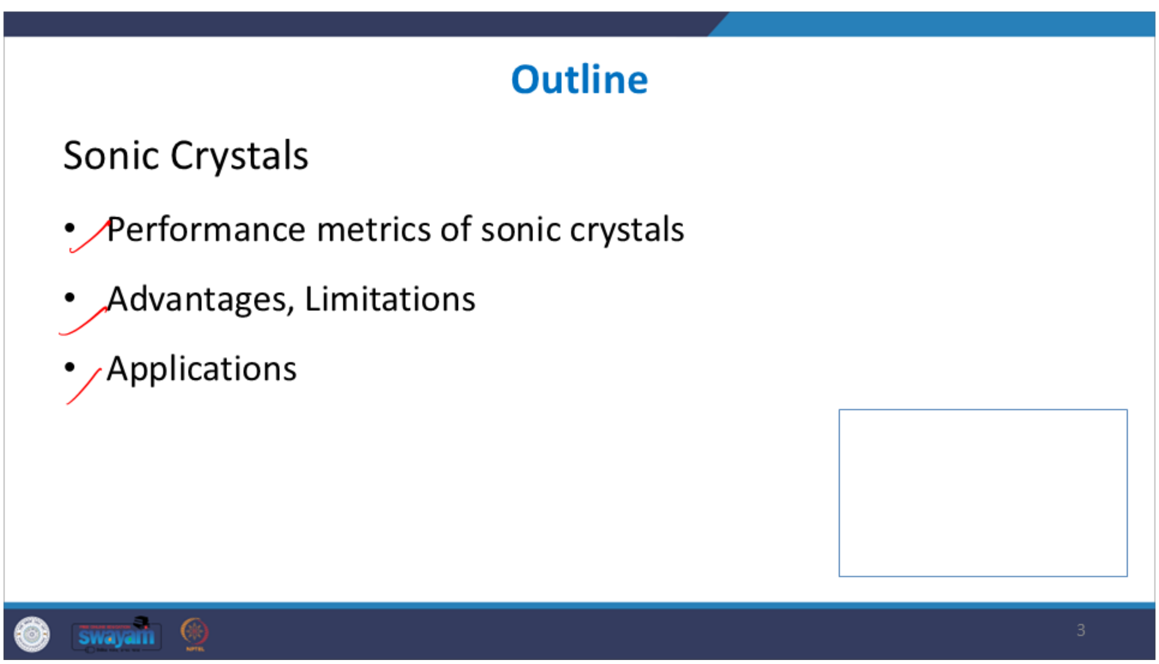
**Lecture:51**

**Lecture 51: Sonic Crystals 3**

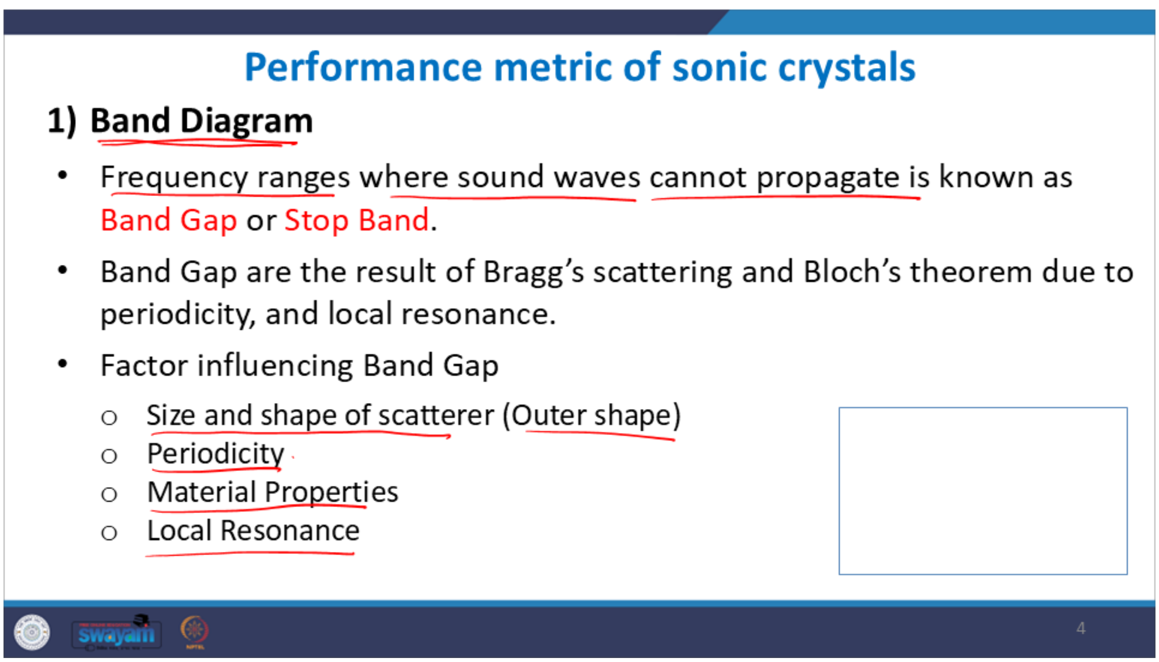

Hello and welcome back to the lecture series on noise control in mechanical systems with myself, Professor Sneha Singh. So, we have been discussing an acoustic metamaterial called sonic crystals—the introduction, the definition of what a sonic crystal is, and the working principle of sonic crystals. in depth So, various concepts like the use of Bloch's theorem and Bragg's law or Bragg scattering, local resonance, and just the generic multiple reflections and scatterings that occur in a sonic crystal. All of this leads to band gaps. What are band gaps? They are the range of frequencies where sound waves do not propagate through a sonic crystal structure. So, these are those frequency bands where wave propagation does not take place. So, somehow the sound waves get attenuated and do not propagate through the structure. So, today, because this knowledge will be required for today's lecture, I have defined



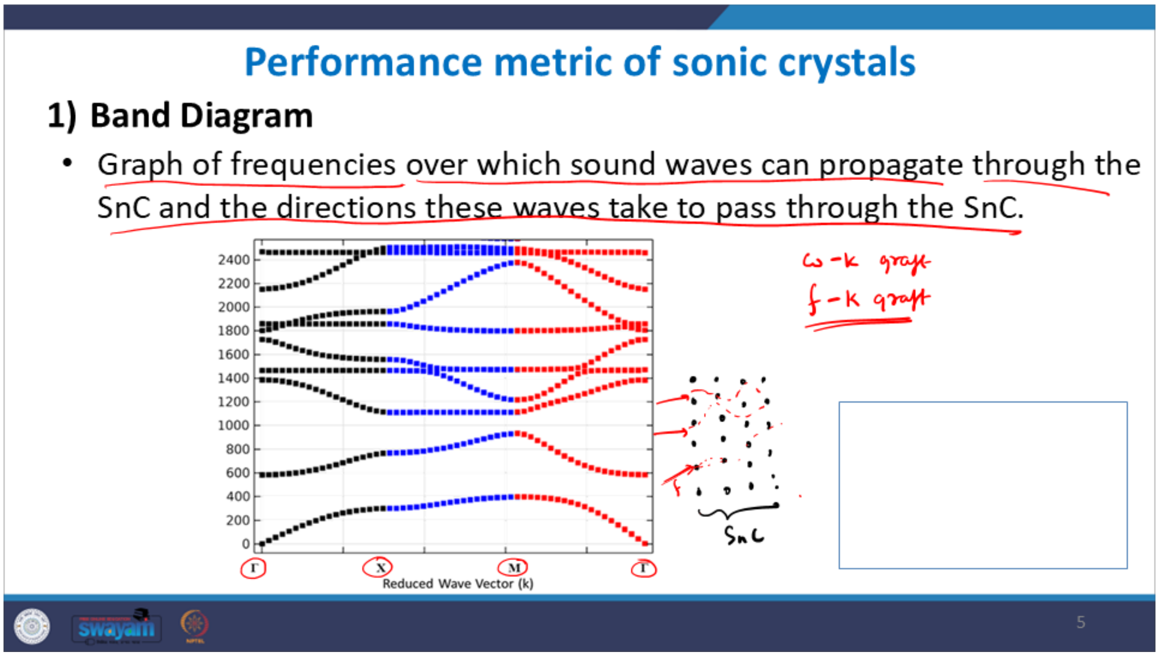

So, today, what we will do, have already covered the working principle. So, we will close the discussion on sonic crystals today with a discussion on the performance metrics of sonic crystals: how to measure the performance, what the advantages and limitations are, and their applications. Let us begin.



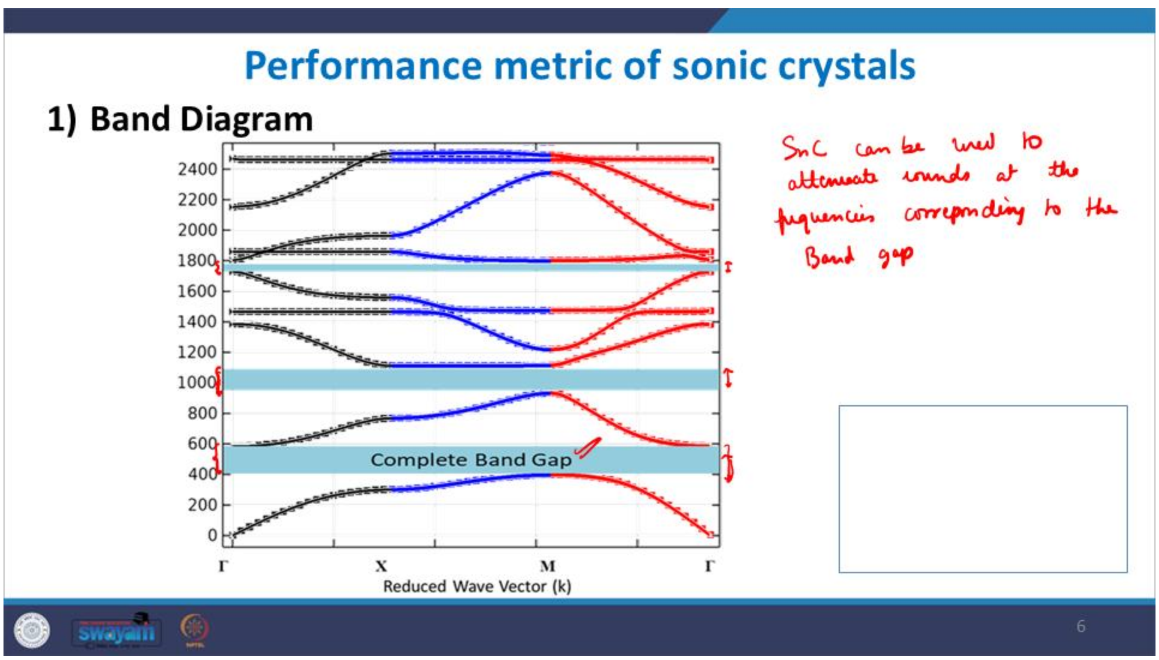
So, the performance metric—the first one is the band diagram. So, usually you know the sonic crystals performance can be measured by plotting a diagram called the band diagram. This has been derived from the solid state physics. In the solid state physics, the band diagram is pretty common. So, what is it? There are certain frequency ranges where sound waves, they cannot propagate through in the sonic crystal. Because of these various working principles, they ensure that the sound wave at certain frequency range gets attenuated and it doesn't propagate through. So, these frequency ranges are called as the band gap or the stop band, which means that this is the frequencies where wave is not able to pass through the crystal. So, the various factors that influence are the size and the shape of the scatterer, what is the outer shape and the inner dimensions, the periodicity, the materials-based properties as well as the local resonance that is happening. Various of these factors influence the band gap.



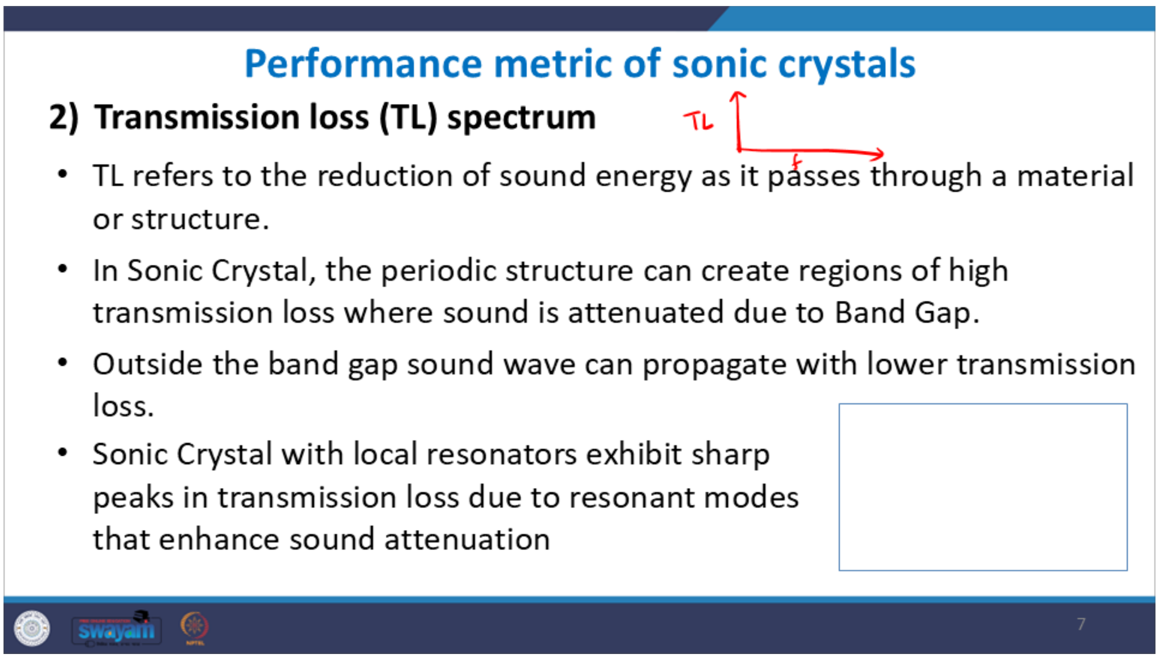

So, what is a band diagram that is used to measure the performance? It is a graph of the frequencies over which sound waves can propagate through the sonic crystal and the directions these waves take to pass through the sonic crystal. Again, for this course at the UG and the PG level, we will not go into detail of the crystal theory and what are these values. This is something which is for your extra reading that if you are interested, you can do, but it is not part or the scope of this course. So, within this course, it is just that a band diagram is what? It is an ω, usually ω-k graph or a linear frequency and k graph. So, what it says is that what are the frequencies and what are the directions they are taking to pass through the sonic crystal to very simply put.



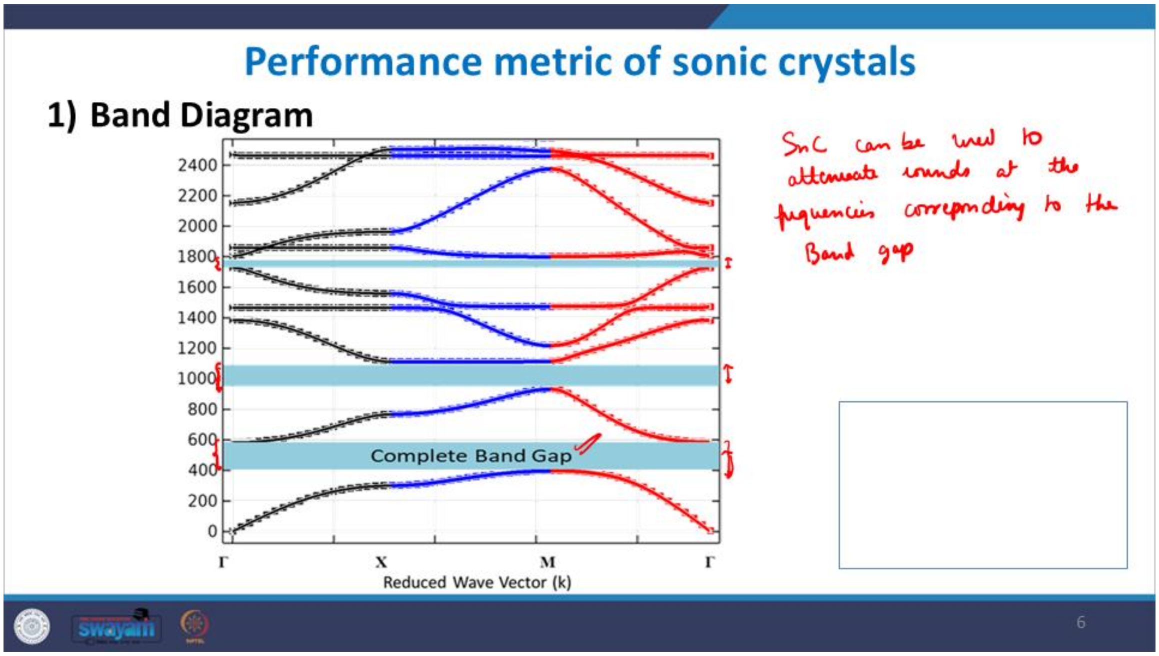

Now, if you notice this figure clearly. you can say that at these frequency ranges okay there is no direction through which the sound wave is passing okay at different frequencies the sound wave can take different directions to pass through the or the different propagation direction to pass through the crystal but at this there is vacant space so what it means here is that in these ranges of frequencies If the sound wave is incident at these frequencies at every direction they will somehow get attenuated. So, they are not able to ultimately cross the structure okay because in the same way you can notice some vacant space here. Again what it means is that if the sound waves are incident at these band of frequencies then no matter how they are incident and what path they are taking they are not able to cross the crystal structure they are not able to cross this entire structure by taking any pathway so there is no k vector associated with them okay because k vector shows the direction the sound waves take to pass through if there is no k vector which means that the sound waves are ultimately not able to propagate through in any possible direction So, what do we call that we call it as a complete band you can see the same thing here. So, from the band diagram we can see the range of frequencies where there is a vacant space the range of frequencies where you have no plots or no dots. Those become your complete band gap. So, the range of frequencies where you have no plot available which means that the waves cannot propagate through in any particle in any possible direction. These are called as a complete band gap. If a band diagram is given to you, Using the band diagram you can find out what the range of frequencies are over here. This is your first range, this is your second range and this is your third range of frequencies over which there is no propagation possible because there is complete vacant space throughout all the propagation vector. So, throughout the k axis there is a vacant space in these range of frequencies and using this band diagram you can predict a complete band gap. So, at these frequencies sound waves do not pass through. So, the sonic crystal can be used to attenuate sound. So, obviously the sonic crystal can be used to attenuate sounds at the frequencies corresponding to the band gap okay because these are the places where there is a gap and no frequency and the sound waves at these frequencies they are not able to cross the sonic crystal at these particular ranges.



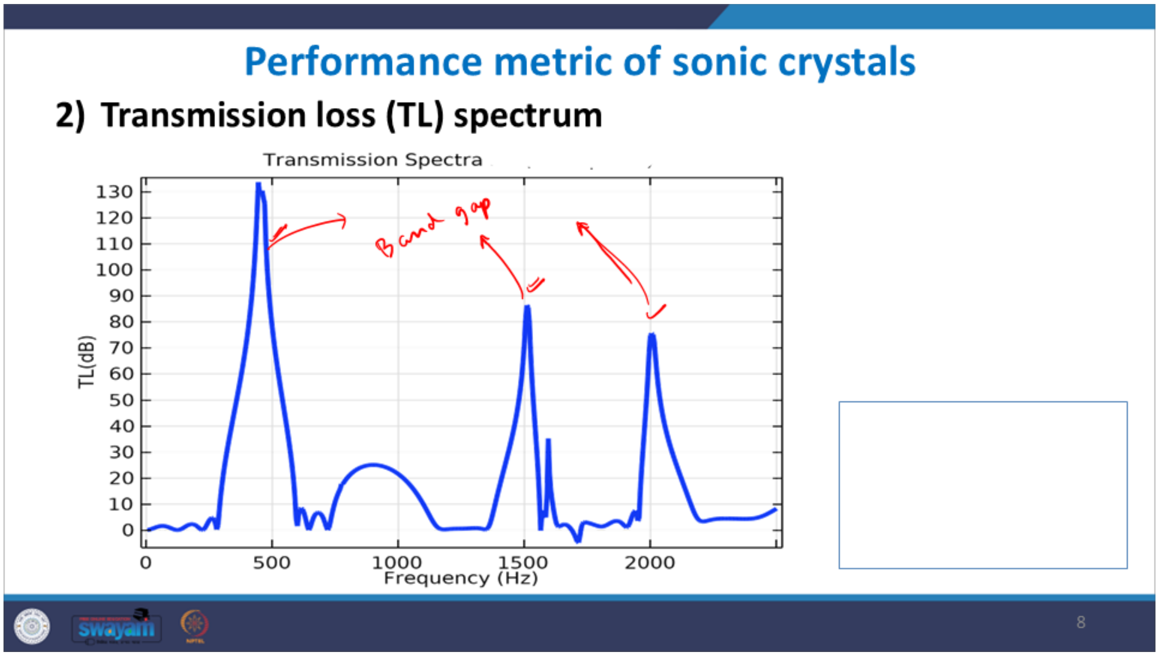

The second kind of metric used to measure is the transmission loss spectrum. We already know what is transmission loss. Transmission loss is simply the sound intensity level. It is simply the sound intensity level of the incident wave by the sound intensity level of the transmitted wave and the higher the transmission loss which means the better the crystal structure is at attenuating those waves. So, TL you know what is TL? So, simply the transmission loss spectrum can be used because transmission loss ultimately is a function of the frequency. So, you can plot the TL versus the frequency graph to see what the sonic crystals are behaving like. Now, if you know that you know this is the band diagram. So, you would be able to guess that the range of frequencies over which you are obtaining a band gap those are the frequencies where sound waves they are not able to pass through. So, that is the frequency where you know there should be a sharp peak in the transmission loss. There is a very very poor transmission at those frequencies because the sound waves they are difficult to pass through they find it difficult to pass through in the band gap. So, that is what can be seen.



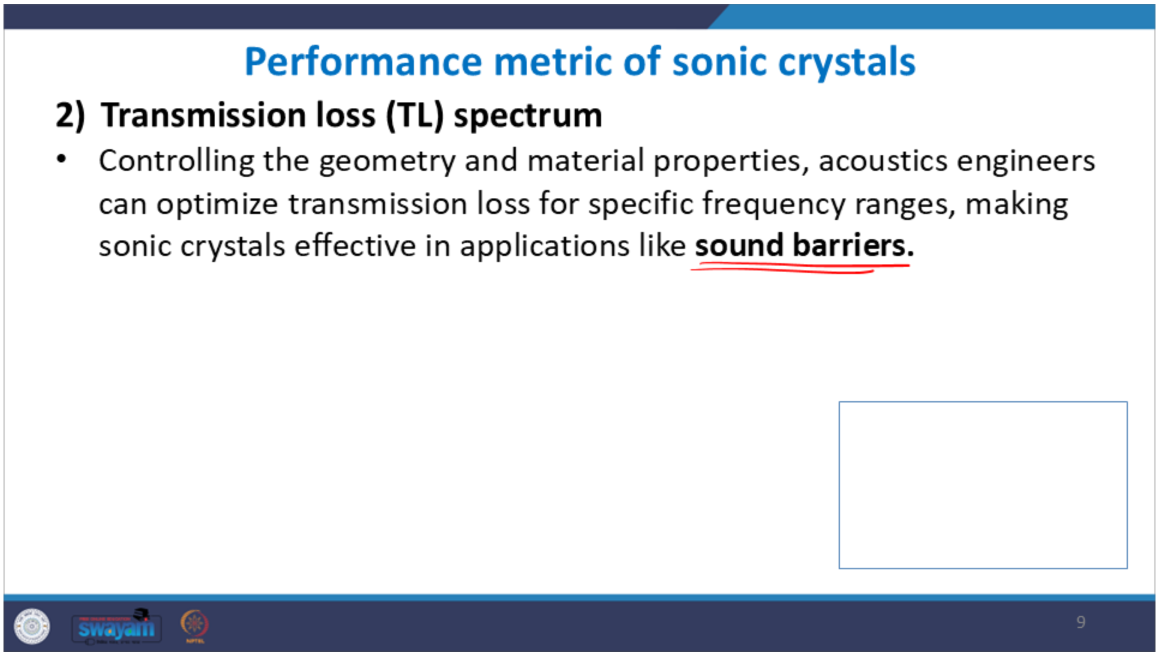

If you see the corresponding structure between 400 to 600, then somewhere centered around 1000 hertz, okay, then somewhere in a very small range near about 1800, less than 1800 hertz,



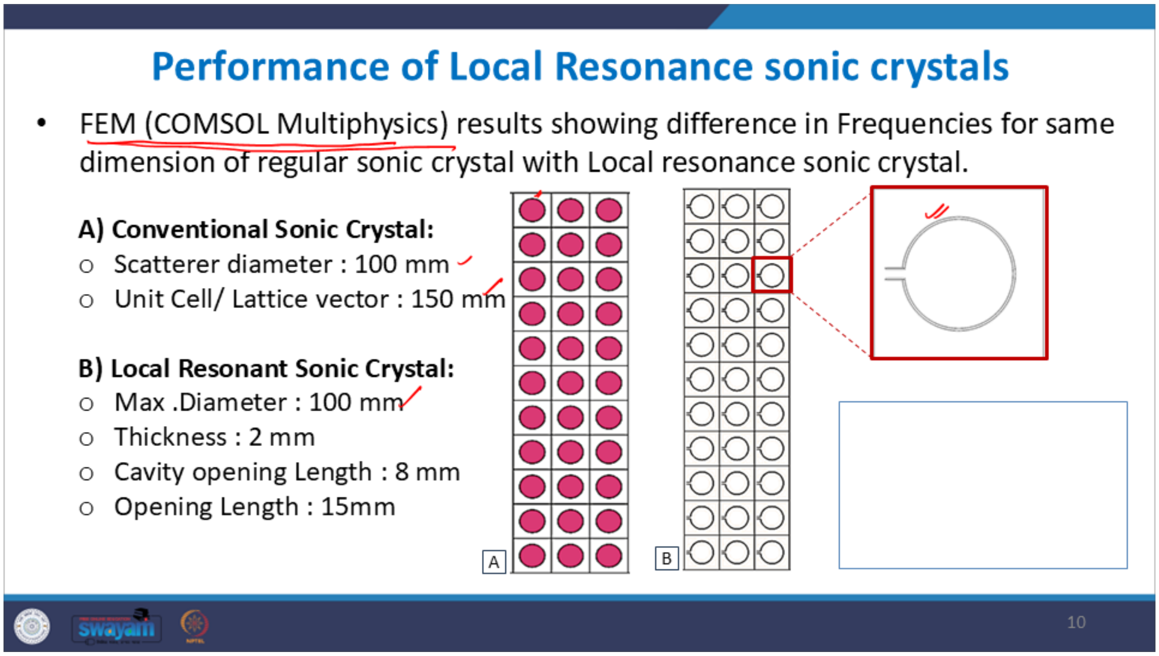

You can see the same things, you know, sharp peaks at these ranges which correspond to the band gaps. These correspond to the band gaps that were observed in your band diagram. That is where you will have because those are the frequencies where wave propagation becomes difficult and hence there is very less transmission and the transmission loss takes a peak at those frequencies. And that is the SNC structure becomes more effective at these frequency ranges. So, this is a typical transmission loss spectrum and you can notice the peaks which correspond to the frequency ranges of the band gap okay.



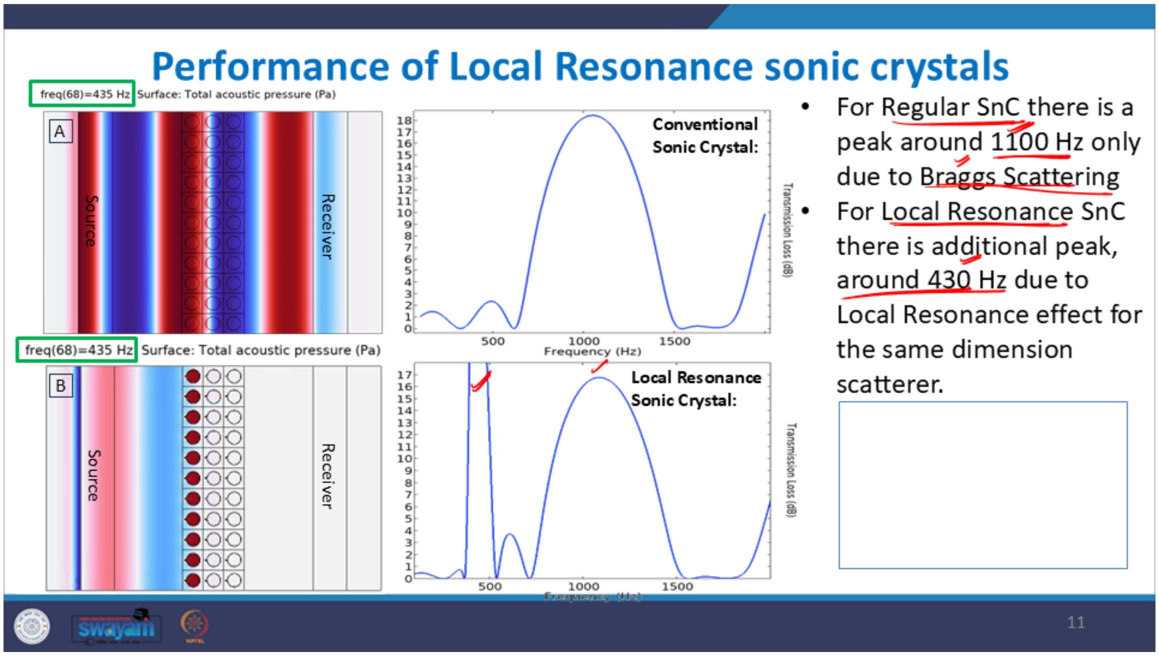

So, controlling the geometry and the material properties the acoustic engineers they can optimize the transmission loss for specific frequency ranges making these crystals very effective in applications such as the sound barriers. So, the band gap as already told depends on what is the periodicity, what is the type of scatterer or the geometry of the scatterer you are using, what is the material of the scatterer you are using. So, if you are able to change these things, you would be able to change or tune the range of frequencies over which you can stop the sound waves. And accordingly, based on what your target range of frequency is. So, suppose you are trying to cut down some road traffic noise, you can measure the road traffic noise and see what the typical peaks in the road traffic noise are, and you can design a sonic crystal structure to attenuate those peaks or to stop the sound waves at those particular ranges of frequencies. In the same way, suppose you are designing some sonic crystal for some high-speed railways. You can measure and find out what the noise spectrum of your source is, what the noise spectrum of that high-speed railway is, and based on what the places are, what the frequency ranges are over which the noise is peaking. You can design a sonic crystal structure where the band gap corresponds to the peaks in your noise spectrum. So, at those peaks, you are able to control most of the noise and not let it pass through.



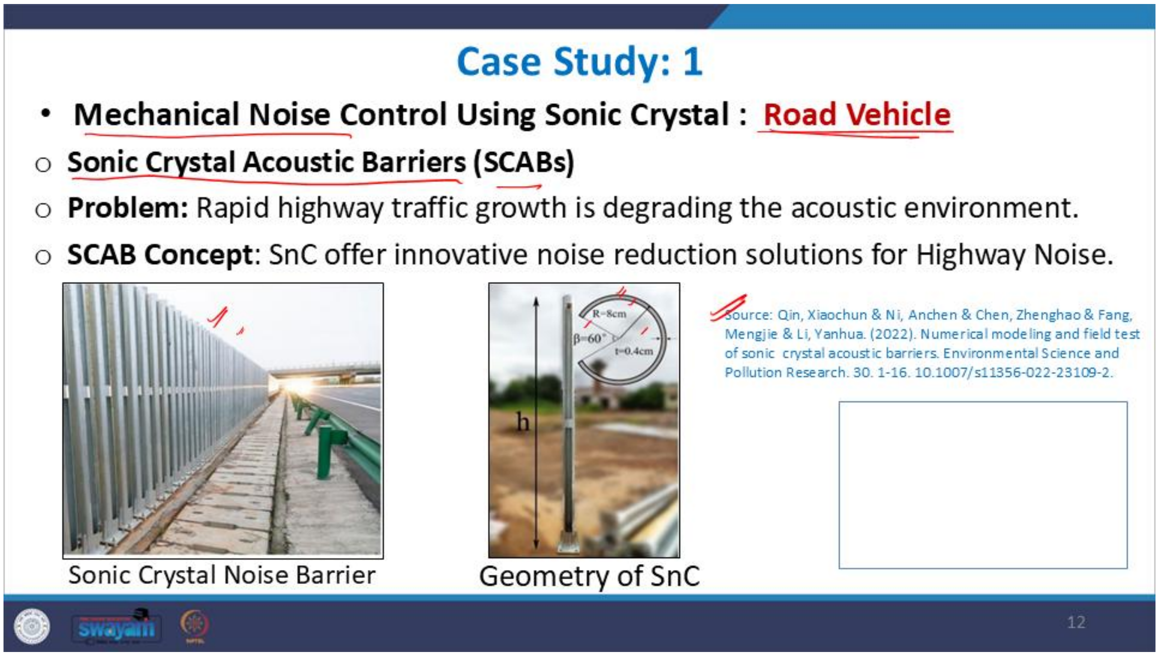

So, let us say here this shows the result of one of my PhD students, and he has done FEM analysis in COMSOL, and here it shows the effect of local resonance. So, we have the same sonic crystal structure—the same outer dimension and the same periodicity—has been maintained for both these structures. The same periodicity, the same outer dimension, and the same outer shape, which is a circular shape. The difference here is that in the first case, the scatterer is a solid cylinder, whereas in the second case, it is like a Helmholtz resonator, a C-shaped Helmholtz resonator. So, let us see the difference in the band diagram for these two structures and the difference in the transmission spectra. So, what you see here is that for the first structure, having all the other outer properties the same, but because it is a solid structure, it is not doing the local resonance. It is not operating on the principle of local resonance, rather just operating on Bloch's theorem.



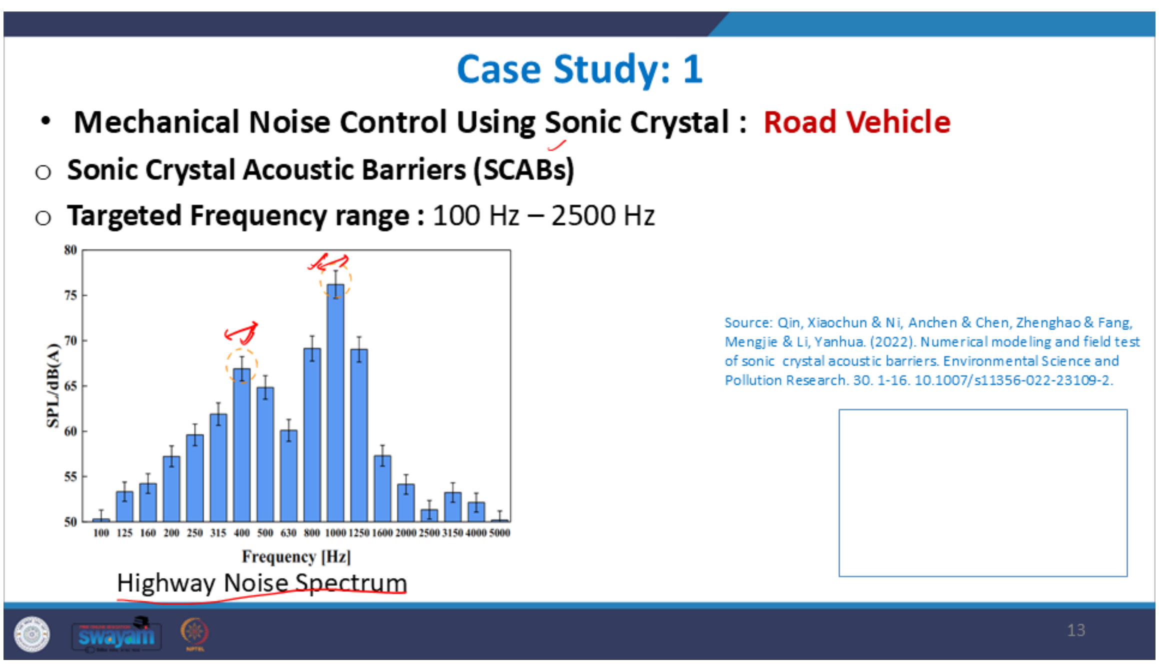

So, for the first regular structure, as per Bragg scattering law and Bloch's theorem, it is able to get a peak at around 1100 Hertz, okay. Whereas, in the second structure, we have changed the scatterer, and now it is not solid, but it has a hollow confined cavity. So, it acts as a Helmholtz resonator. And now in addition to the Bragg scattering and the other phenomenon in addition to that it is using local resonance and it is getting an additional peak at a much lower frequency of 430 hertz here a very high peak because resonance leads to a very high peak. or a very sharp attenuation very kind of high attenuation and you can and the remaining peak is the same okay so this shows the effect of local resonance which you can clearly see through the transmission spectra.



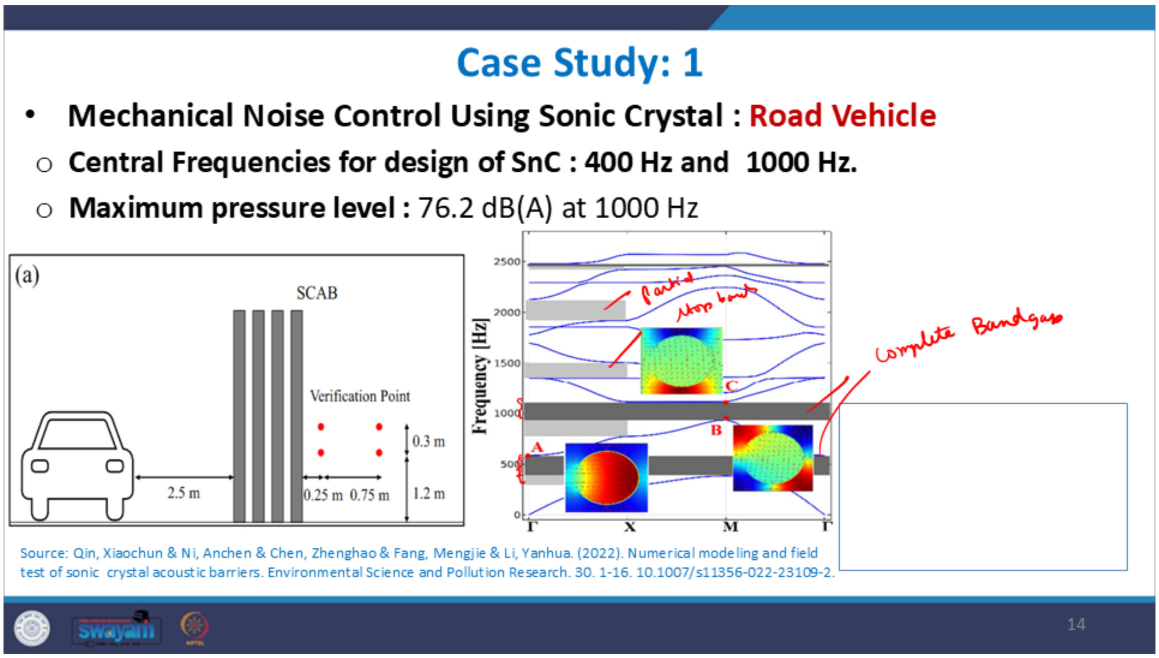

Let us see some of the applications of sonic crystals what are the applications the major application is in the field of noise control it can be used as a noise barrier okay to cut down highway noise train noise, roadway noise, etc. So, it can be used as a barrier. So, here this first paper, the source of this figures is from this paper and here what they have done the authors, they have used it to control some mechanical noise of a road vehicle. So, they have measured the road vehicles and they have made a sonic crystal acoustic barrier. This shows this structure and the problem was that the rapid highway traffic growth is degrading the acoustic environment and they created a sonic crystal structure which is at the end it is like a fence structure at the end of the either end of the road so that the traffic noise does not propagate through into the surrounding areas from the road. okay. So, what is happening here? The individual you know this shows the each of these resonating elements. So, here it is a collection of these cylinders and what were the cylinders like? They were like a C shaped cylinder. So, they were hollow C shaped cylinder and this shows the dimensions of each of these cross section of the cylinders which were placed in the to make the sonic crystal.



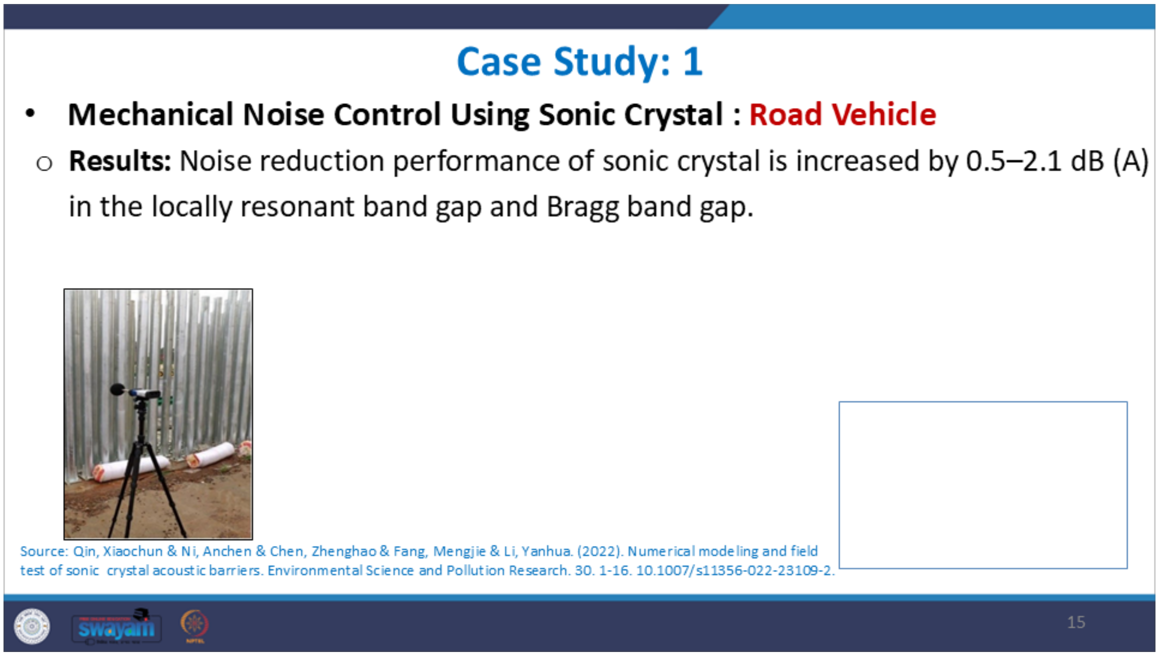

The target frequency range when it was measured this was chosen as you know the target range between 100 to 2500 hertz with the peaks observed at these frequencies and the SNC this sonic crystal barrier was designed to attenuate these frequency ranges because this was the noise spectrum of the highway. So, this is the kind of structure and you can see the band gap. The band gap corresponds to the first peak is centered around 400 Hertz, the second peak is centered around 1000 Hertz.



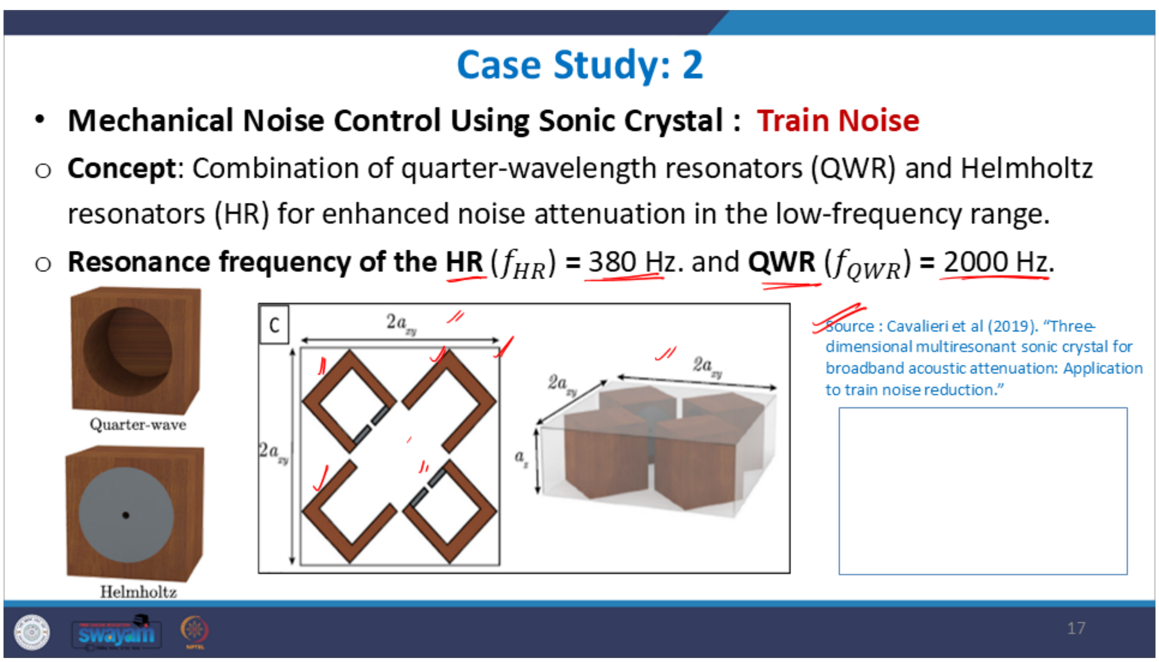
So, the way they designed the sonic crystal so that the first band gap was obtained centered around 400 or 500 Hertz and the second band gap was centered around 1000 Hertz. So, there was complete band gaps in these frequency ranges. complete stop band and then there was some partial stop band in these ranges. So, they were able to design the structure whose performance was centered or whose band gap was centered around the noise peaks observed in the highway.



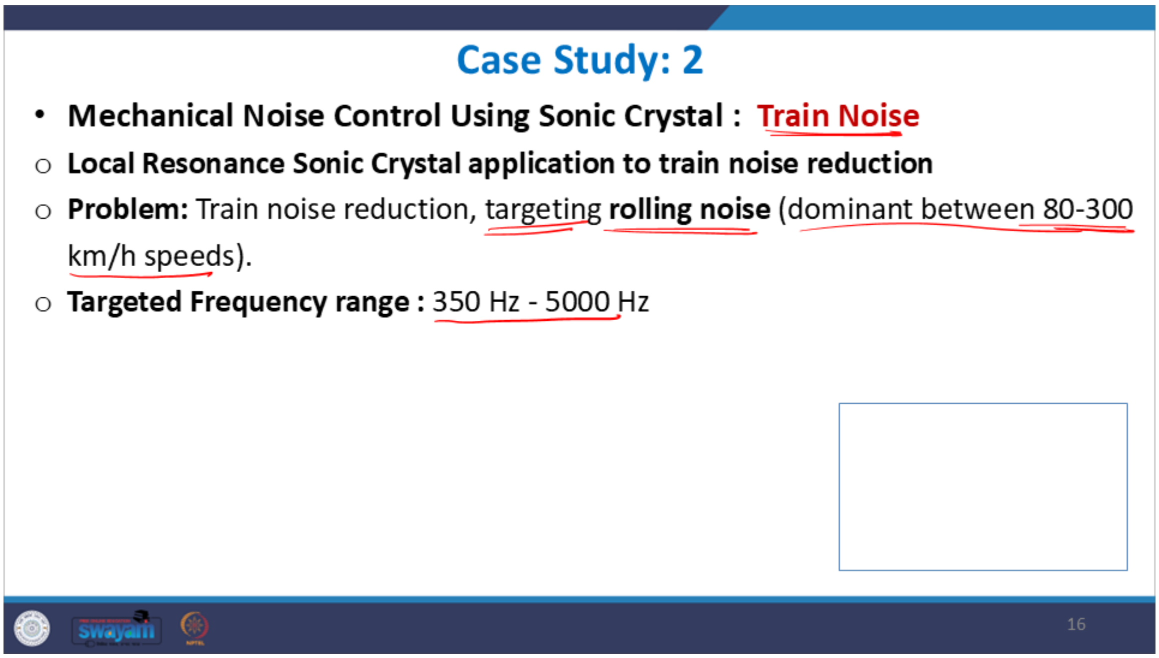

And the results is they were able to reduce the just by incorporating the sonic crystal with the local resonance they were the local resonance led to an additional increase in the noise reduction performance.



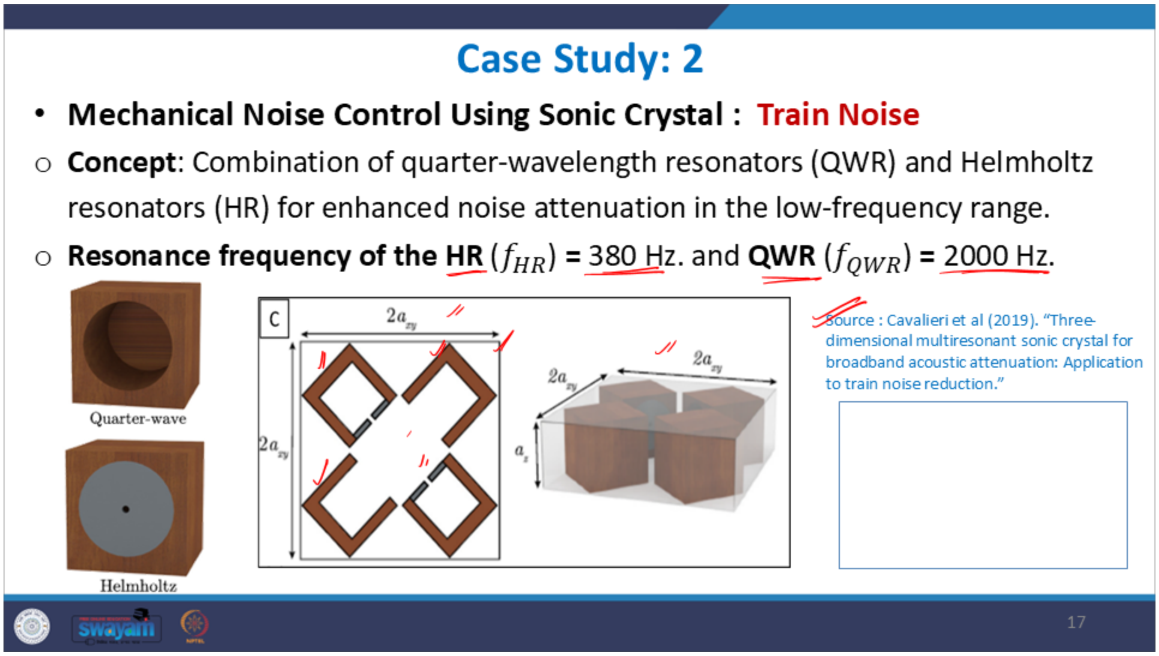

Okay, another case study, this is again taken from some paper, that is the paper, that is the source of the paper.



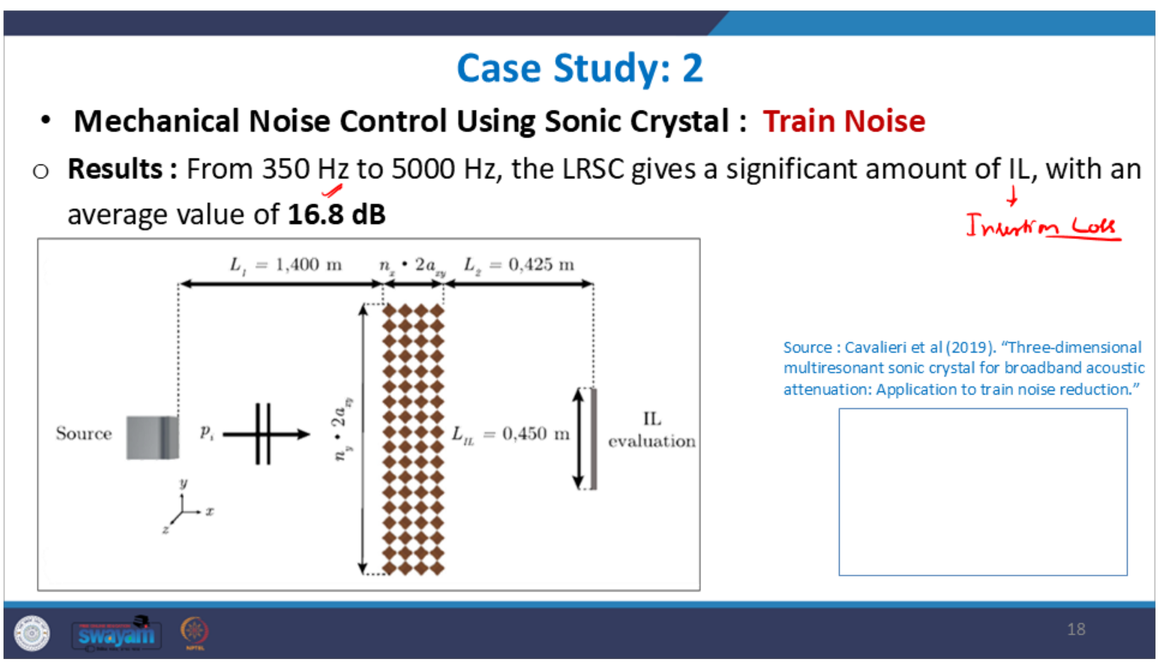
So, what happens? A local resonance sonic crystal was used to reduce the train noise here. So, the train noise reduction and the target was mainly to focus on the rolling noise and you know that for most of the vehicles you know sorry the rolling noise is more dominant it was found that for the train the rolling noise was the most dominant between 80 to 300 kilometers per hour speed and the solution based on sonic crystal was to target these rolling noise. And the target frequency range was between 350 to 5000 Hertz. Okay.



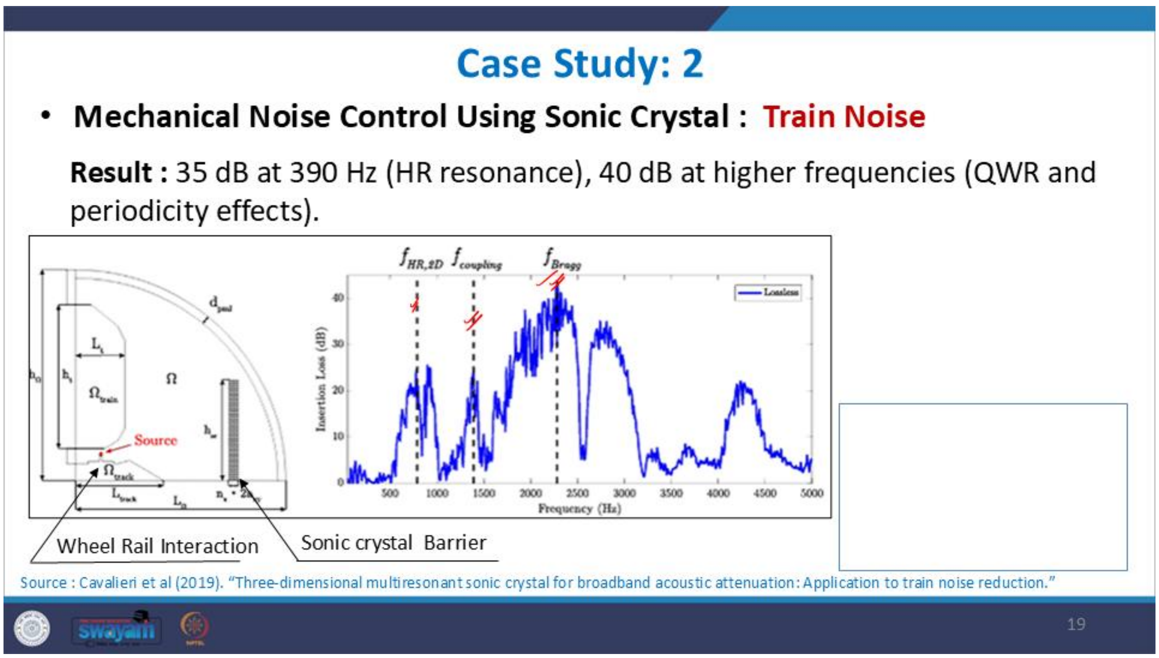

Let us see the concept and the design of this. So, what was the sonic crystal made of? So, it was made of one unit cell and then an array of these can be made. So, within a single unit cell, you had four separate resonators. Two of them were quarter wave resonators which is think of it a cavity with an open neck that becomes a quarter wave resonator and the other two were Helmholtz resonator where you had a confined air cavity with a small neck. So, they were arranged in this kind of pattern to get a unit cell. So, this is a typical unit cell in 3D and this shows the 2D view and this kind of sonic crystal consisting of quarter wave resonator and Helmholtz resonator within a scatterer was used. So, this shows one scatterer. So, here the resonance frequency of this Helmholtz resonator was 380 Hertz, whereas for the quarter wave resonator it was 2000 Hertz, so that it can cater to both the lower and the higher frequencies.



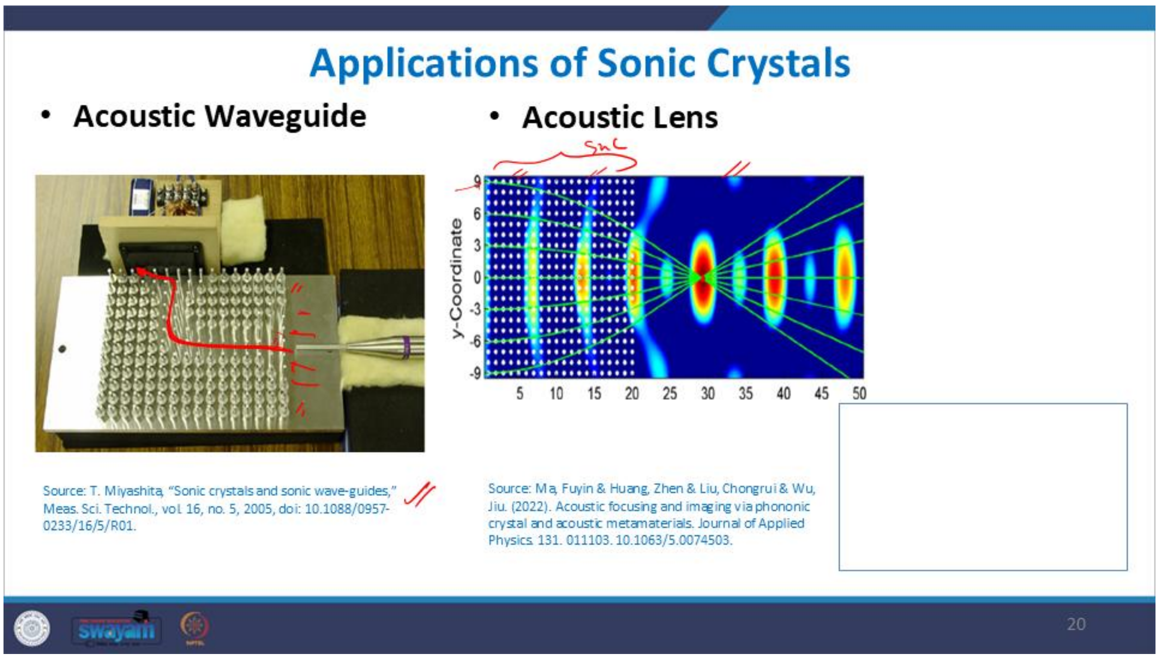

The results were obtained using the sonic crystal and a big 16.8 dB of insertion loss was observed when these sonic crystal barriers were installed. So, this was a huge reduction. insertion loss ok.



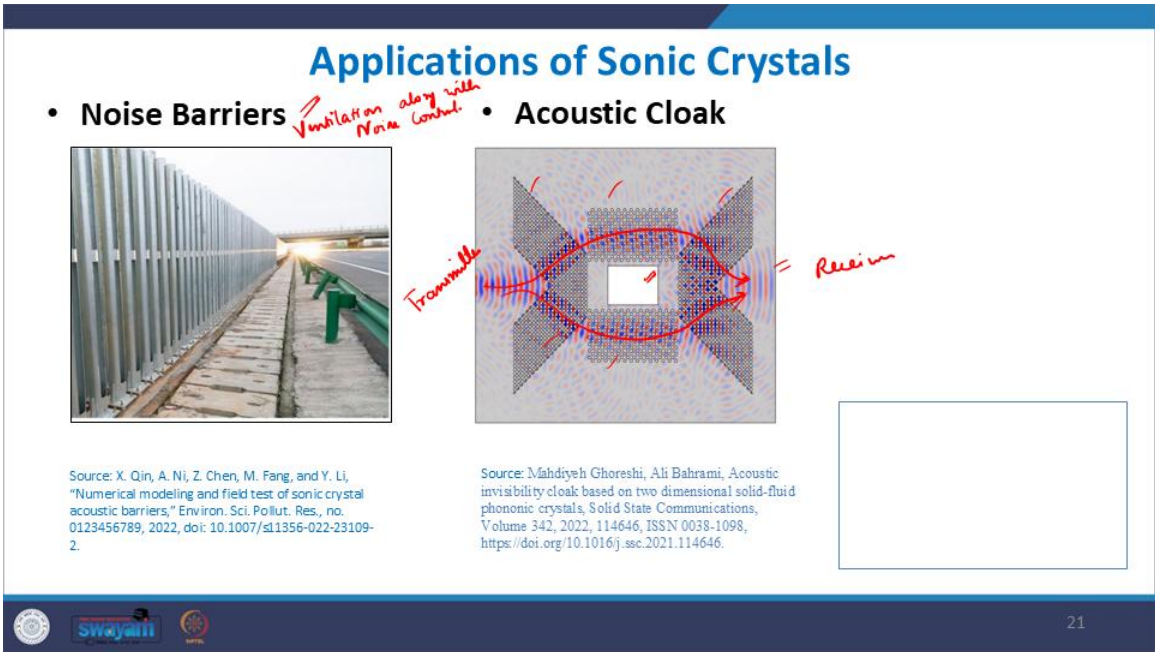
And this shows the typical transmission spectra as you can see due to the Helmholtz resonator you know the resonance is obtained at a lower frequency and quarter wave gives at around 2000. So, this is due to the you know quarter wave resonator, this is due to the Helmholtz resonator the lower peaks and then there is also an additional peak due to the coupling between the two. So, various kind of transmission loss peaks were obtained.




So, these two case studies were based on the applications of sonic crystal as noise barrier. So, that is but not just as noise barriers and for sound attenuation the sonic crystals can also be used for various other purposes such as they can be used as acoustic waveguide. You can see here what is an acoustic wave wide. Already I have told you just like you have optical fibers to direct the light waves. Acoustic wave wide is a structure made to direct the sound waves. So, here the sound waves they can be directed along this path whatever is the intended path and they can go most of the sound waves which are being incident. will be directed along this path. So, the waveguide can be made and how it is made is that you can make a sonic crystal and within this as a regular array of certain you know scatterers and within that crystal suppose you want to create a waveguide and you want to redirect the sound along a certain path. you can introduce some kind of defects. The defects could be in the form of removal of scatterers or the change in the property of the scatterers or the change in the dimension of the scatterers and if these kind of defects are introduced, the waves get trapped in these defects and they are redirected along the path of the defects. So, this acts as a wave guide. It can also be used as acoustic lens to you know focus the sound waves. This shows a typical you know contour where you know the sound waves are first hitting this sonic crystal array. This is your sonic crystal array and slowly they are focusing and they are getting focused in this small zone at this particular kind of distance okay and the focusing is happening.




They can definitely be used as noise barriers which is the most common application and as noise barriers they are able to provide ventilation along with noise control compared to the traditional noise barriers which are made of wood, cement, etc. This also provides ventilation. They can also be used as, you know, an acoustic cloak. What is an acoustic cloak? Suppose a device has to be hidden. Especially in stealth technology in defense, you need your submarines or various other things to be hidden and undetectable by sonar or any kind of acoustic detection method. So, if you want your structure to be undetectable by sound waves, then this particular thing has to be hidden. So that the sound waves are not able to detect it using the sonar technique. Then, around it, you know, the area of scatterers—the sonic crystal structure—has been built such that the sound wave is made to just pass through it and then regain its original wavefront. So, no reflection—they just pass all around it and then regain their original wavefront. So, from the transmitter at this end to the receiver at this end, it feels like there is no change in the pattern—there is no reflected wave—but it seems like there is no object, and it is just passing through. So, this is the principle behind the acoustic cloak.




So, with this, I would like to close this lecture on sonic crystals, and next class, we will solve some problems based on it. Thank you for listening.