NOISE CONTROL IN MECHANICAL SYSTEMS

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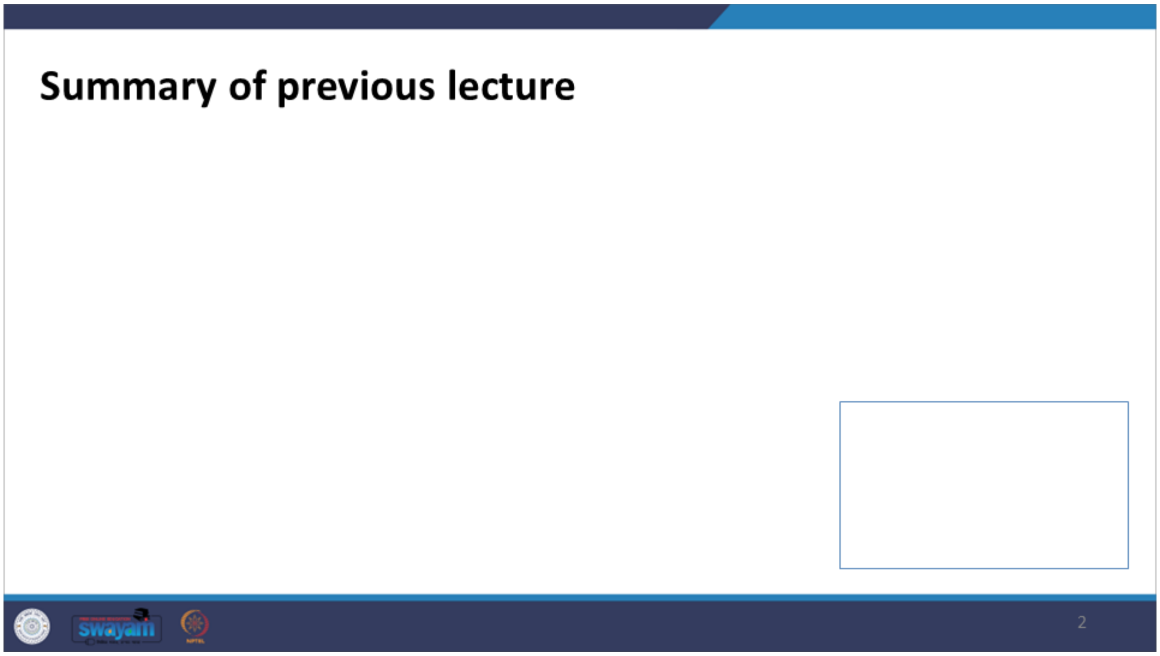
Week:10

Lecture: 48

Lecture 48: Space Coiling Acoustic Metamaterial 2

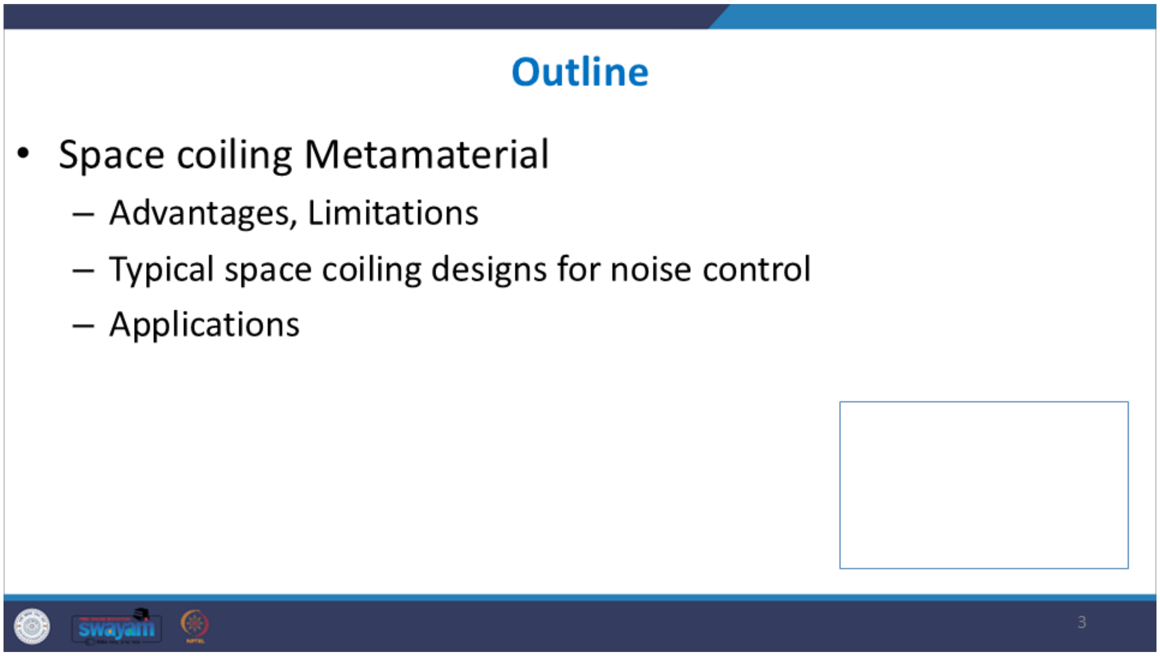
Hello and welcome to this lecture series on noise control in mechanical systems with myself Professor Sneha Singh.

So, we have started discussing in these lecture series on the concept called as the acoustic metamaterials and one type of the acoustic metamaterial is the space coiling metamaterial which is a metamaterial which it's a kind of a passive metamaterial and it uses the design so what it does it starts when the wave is incident on it the internal structure of the metamaterial is in the form of maze like pathways so it forces the sound waves to go through these maze like pathways so that within a small physical size the sound wave has to take much longer pathway so something like this the wave is entering and suppose we have some metamaterial like this and this shows the inside geometry of the metamaterial and the kind of pathway the sound is taking.

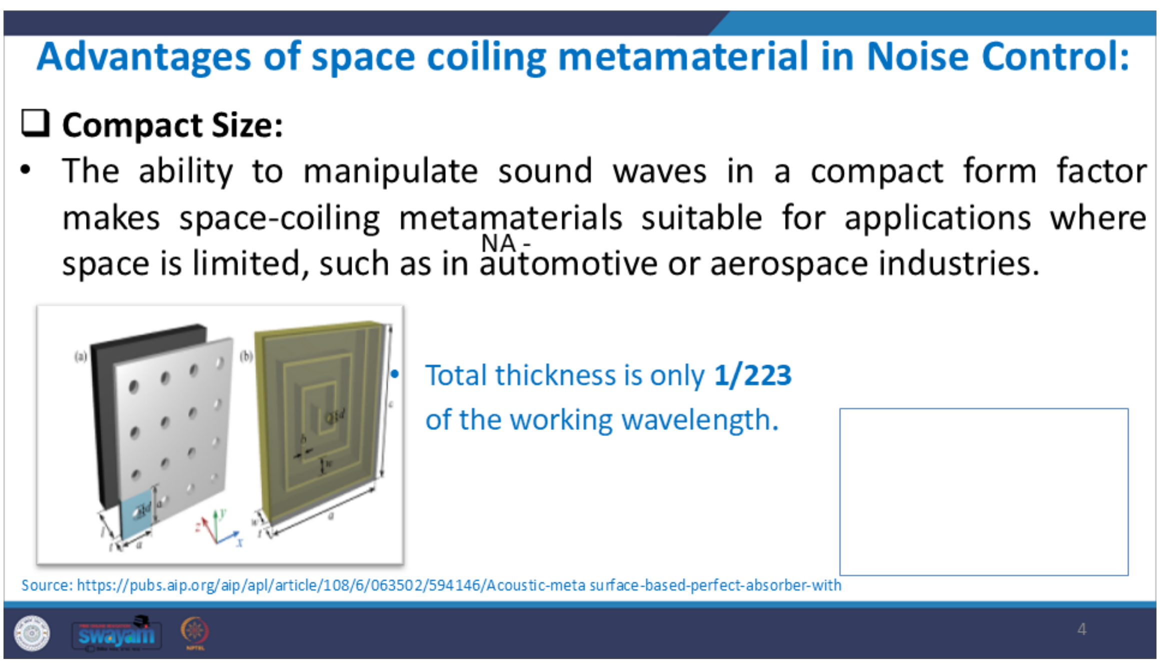


Finally, when going outside of it, so instead of going in a straight line path, now the sound wave has to take a much longer path which leads to the slowing down of the speed. So, the assumed, so from traveling from point A to B, it takes a much longer time for these waves to go and it sorts of delays the wave. and slows down so it leads to phase delay the slowing down of the speed and it increases the interaction of the waves with the internal structure which leads to more deflections and then if suppose a structure is closed it can act as a you know a long pipe which can have its own resonance frequency. So, last class we derived about the what is the resonance frequency for a space coiling metamaterial and at those frequencies There could be large vibrations in the air particles inside the labyrinthine structure which can lead to further sound absorption at these frequencies.

So, we studied about the phenomenon of resonance. and also something called as impedance matching which happens when the sound waves are incident at the resonance frequency. So, they are able to freely enter because the surface impedance of these metamaterial becomes very close to the surface impedance of the air itself. and that is why there are minimum reflections most of the wave is able to enter inside the material at that at this resonance frequency and then inside it it's get trapped within this small compact size structure. So, the working principle has already been discussed and what are these metamaterials today we will simply look at the advantages the limitations



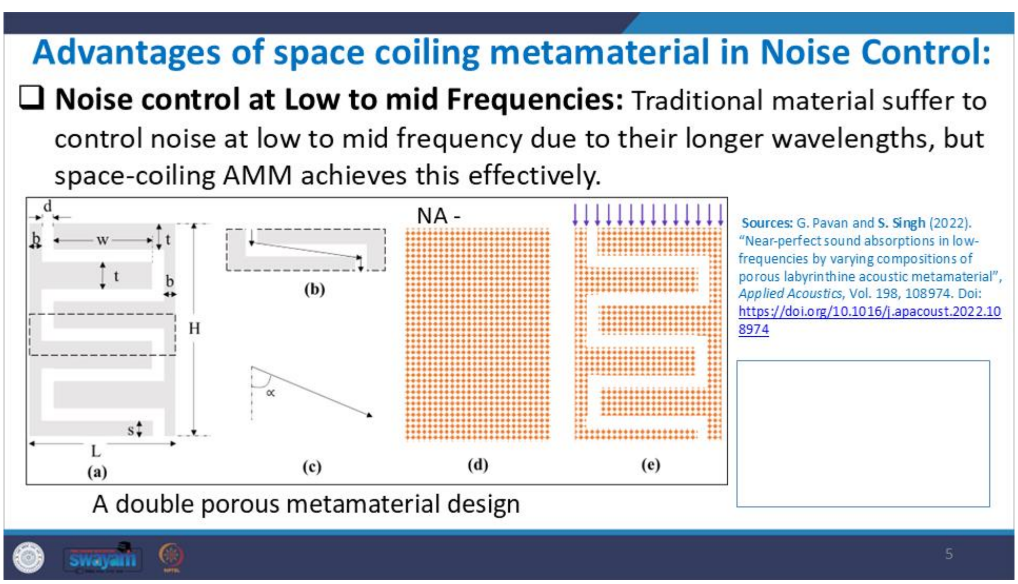
As well as some of the typical space-coiling designs used for noise control and some applications of these space-coiling metamaterials. So, let us start with the advantages in terms of the noise control that can be used in mechanical systems. So, firstly, they have a very compact design, OK. So, right from the very beginning when we started discussing these space-coiling metamaterials, it was said that within a small physical size, we have such elaborate pathways that the sound wave actually travels through a lot. longer pathway, but it is confined within a small space.



So, compactness is one of the key characteristics and one of the key advantages of these metamaterials. And sometimes, so let us say in most of these lectures, I will be referring—because these topics are very new—to the recent research papers that have been published. to give you a context and try to relate the properties with what has been found in the research papers. So, for example, here in this paper, the total thickness is approximately 1/223 times the working wavelength. So, sub-wavelength was the term introduced in the last lecture.

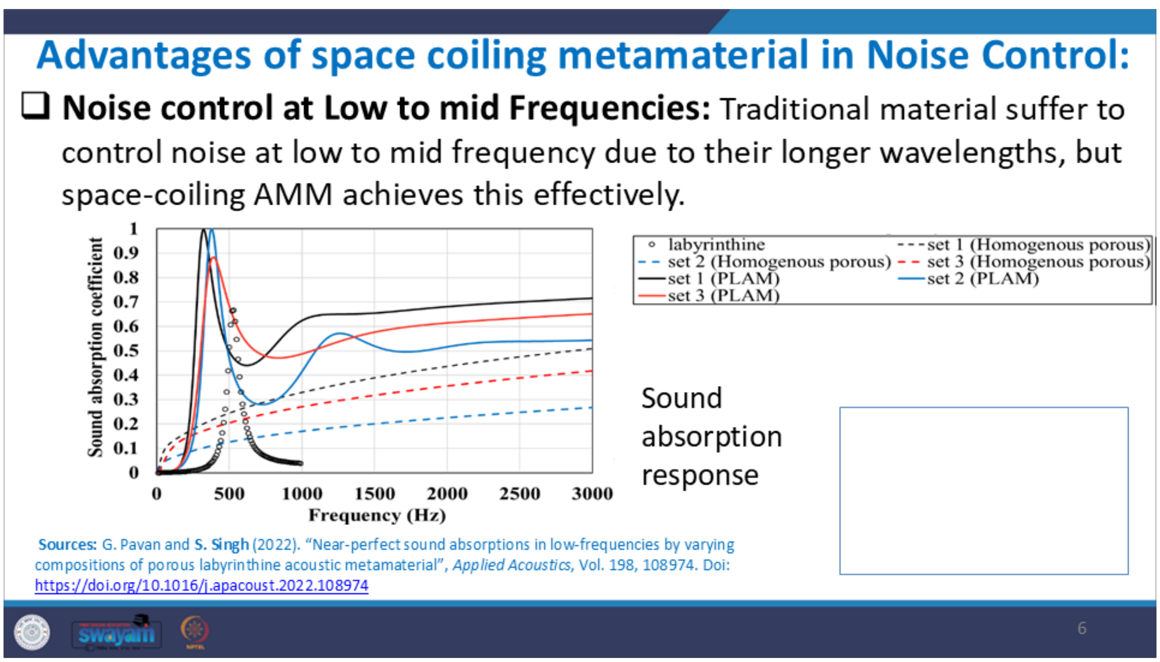
So, what it shows is that most of the metamaterials behave. Extraordinarily when the dimensions of their unit cells are much smaller than the wavelength of the sound waves they interact with. So, the thickness is so small—it is almost 1/223 times the working wavelength here in this case. Whereas, for traditional materials to reduce the same amount of sound wave with a wavelength of lambda, it will need d approximately of several orders of lambda. So, at least several times lambda is required for a traditional material.

So, that is why for low-frequency waves we need a much larger volume, whereas the same thing can be achieved with a space-coiling metamaterial at a much thinner dimension. Then, noise control at low to mid-frequency—so obviously, you know, this is just a takeaway from the previous one—because the dimensions have to be much smaller in magnitude than the wavelength. This is for the space-coiling AMM, whereas for traditional material, the dimensions have to be at least several times the lambda, and hence when the frequencies are low, that means the lambda is quite high, and for traditional materials, then the dimensions required to reduce that low-frequency sound—the dimensions have to be much greater than lambda, whereas with the space-coiling metamaterial, the dimension

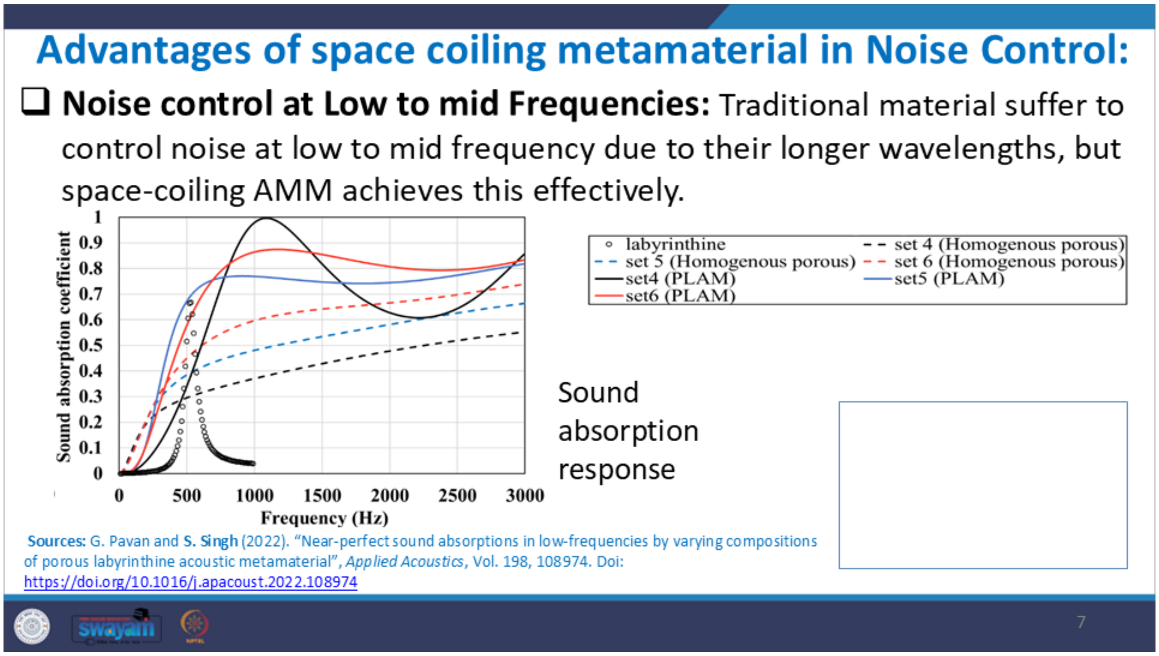


can be smaller than lambda—much smaller than lambda—overall dimension, and in the compact size, we can help in attenuating. So, hence, low-frequency to mid-frequency noise control becomes an essential part or essential advantage of these space-coiling metamaterials. Now, here in our research group, we have been doing, you know, research work on space-coiling metamaterials. So, I will refer to some of the results which we have found—the source of the paper can be seen here. So, what we see here is that we had devised a space-coiling metamaterial which was a combination of this labyrinthine-type structure embedded within a porous region, okay.

So, we had a porous region, and this And within that, we had embedded a space-coiling pathway or a labyrinthine pathway. So, what do we see here? If we compare the sound absorption only by this homogeneous porous material, and then we compare the sound absorption when inside the homogeneous material there is an additional labyrinthine space-coiling structure, So, what is seen here is that for the homogeneous porous materials, which are given by these dotted lines, the sound absorption is quite low. You can see that, you know, the sound absorption was very low even at frequencies of 1000 hertz, 1500, or 2000 hertz.



Whereas, with a proper tuning of the geometry of the labyrinthine structure we were able to get some you know peak resonances at low frequencies you can say these are below 500 Hz for these. So, this is like there were able to give we are able to get high sound absorption peak even at much lower frequency below 500 Hz. Whereas, for the homogeneous porous case, so if only there was homogeneous porous material, it was not obtained. But when a labyrinthine was embedded in the same homogeneous porous material, suddenly there was a big rise and a peak observed at lower frequencies for the corresponding homogeneous material. In the same way, here also this is the

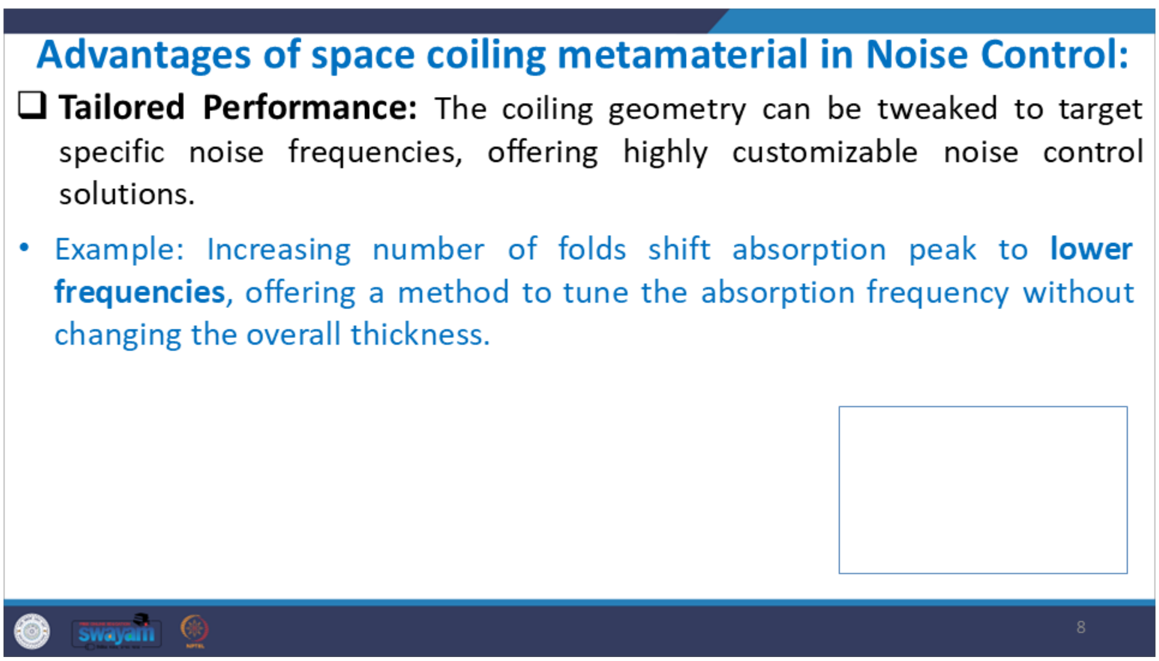


more advanced homogeneous porous materials were used which had better sound absorption capability, but even they had lower absorption below 1000 Hertz and if in the same homogeneous porous material. So, here blue dotted homogeneous porous material when a labyrinthine was embedded then it went to this solid blue lines and similarly in the black dotted graph which represents another set of homogeneous porous material if a labyrinthine structure was inbuilt inside this porous material the SEC graph it went to this black solid lines. And for the red one, for the homogeneous porous material, this was the SAC graph. Once we incorporated a labyrinthine pathway, then for that same material, the SAC became this graph that is a solid red.

So, you can see that in all these cases, whether these three cases if you see or these three cases, in all of these cases what we found was that if you incorporate a space coiling structure, it leads to an enhanced structure. absorption at low frequencies. Ok. And if the structures are properly tuned, sometimes even the range of the frequency can be broadened up. Then another advantage is the tailored performance you know the coiling geometry can be tweaked to target specific noise frequencies offering highly customizable noise control solutions okay. So, the sound absorption is highly dependent or very sensitive to certain geometrical parameters of the space coiling metamaterial because the geometry is very important how the sound waves are moving around okay.

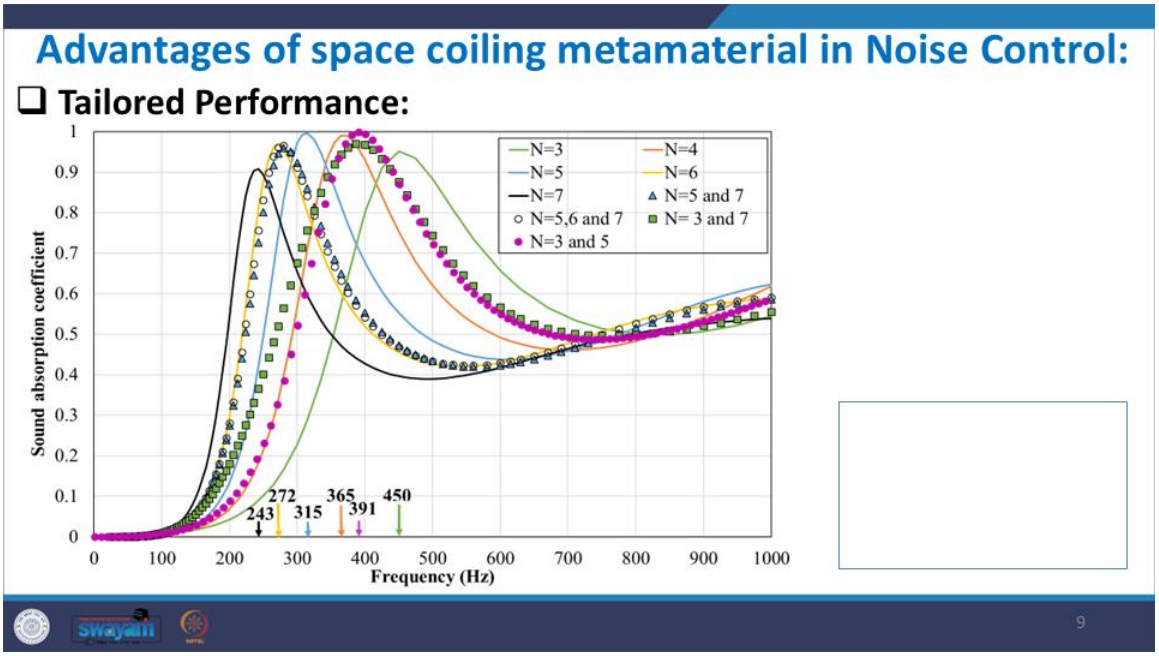
So, here instead of the base material, the geometry plays a more important part, and by tweaking some geometrical parameters, you can change and shift its absorption characteristics. Accordingly, you can get a very customized noise control solution for different problems. So, again, I will refer to the various research already going on regarding how the different geometrical parameters affect the sound absorption coefficient. From one of our researches, what we have found is that suppose we have this kind of space-coiling structure where the sound takes this twisted, turned path, and if we keep increasing the number of folds. So, here you have one fold. 1, 2, 3, 4, 5, okay, like that.

So, if you keep increasing the number of folds, what it leads to is an overall elongation of the labyrinthine pathway. So, let us say we compare two structures. In one structure, the sound wave is moving like this, and in the other structure, we have increased the number of folds. So, the outside dimension is still the same; only inside have we increased the number of folds. With this, we are able to shift the peak frequency to a lower side.

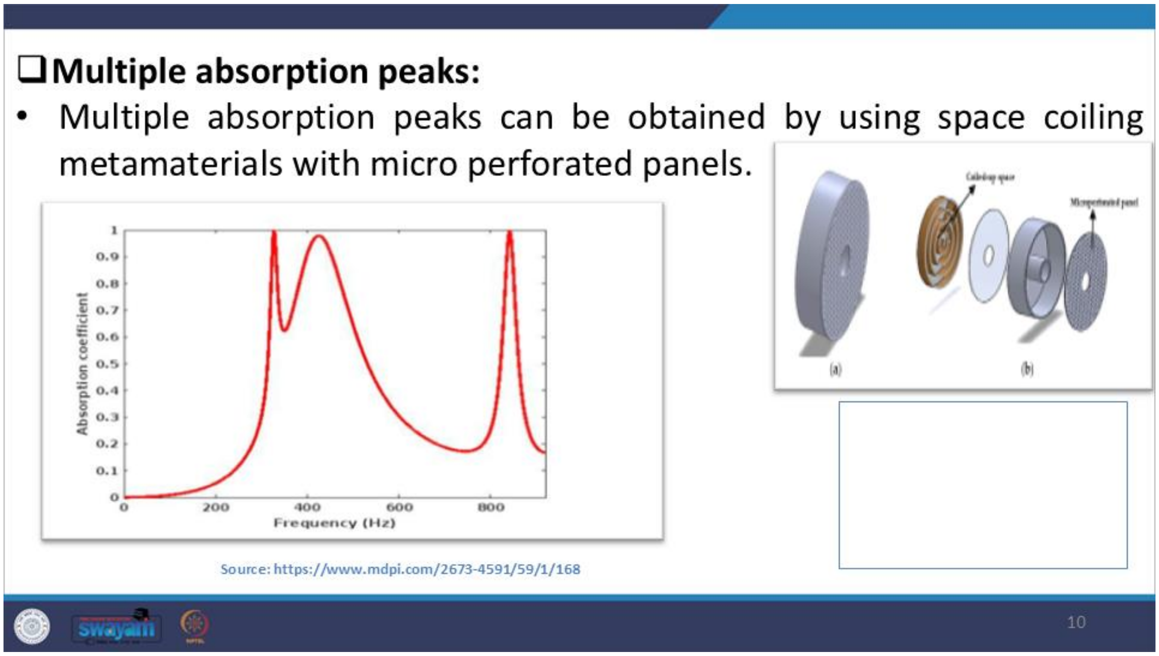


Why? In the last lecture, we have already seen that the peak frequency, the resonance frequency of a space-coiling metamaterial, is inversely proportional to the net length that the sound wave takes because, you know, it is C by, you know, 2 L—sorry, it is (2N + 1) times C by 4 L. So, these are the odd multiples of C by 4 L. So, it is inversely proportional to the length. So, if you keep increasing the length, if this is increasing, this is going to go down. So, if you increase the number of folds, the sound absorption peak then shifts toward the lower frequencies, okay? As you are increasing the number of folds, the length that the sound wave takes is getting elongated because it is now taking a more, you know, elaborate pathway.

which is leading to the shifting of the low sound absorption frequencies to the lower end while maintaining the same outside dimensions. So, here you can see again this is taken from one of the same papers over here. The same paper that I am referring to, so I am taking the results from the same paper and referring to the various properties. So, in the same paper, what we have found is that as we increase the number of folds, the sound absorption peak keeps shifting towards the lower frequencies with the increase in N, as you can see. So, accordingly for the same material having the same overall outside thickness, just by increasing the inside folds in the inside geometry, we have tailored the performance; we have changed the performance of the metamaterial.



Then another advantage could be, just like we can tailor the performance, we can also obtain multiple sound absorption peaks, and without adding any extra volume, we can still end up adding multiple peaks. Now here I will say that suppose we are using a Helmholtz resonator; even in the Helmholtz resonator, we can obtain more peaks, but we need an array of Helmholtz resonators. This is going to increase the weight and the volume because we are adding an additional element. Whereas in the case of the space-coiling metamaterials, without increasing the overall weight, without increasing the overall volume, within the same structure, just by changing some parameters, we can obtain multiple peaks also. So here, this kind of structure was proposed in this paper, and



what they have seen is that Here, the labyrinthine pathway is covered on the top by a micro-perforated panel.

So, here an MPP is being combined with a space-coiling structure, okay. And so, the sound wave first passes through the MPP and then enters into the space-coiling structure, and if you change the hole diameters of the MPP. So, there is one peak corresponding to the MPP and then an absorption peak corresponding to the space-coiling structure. And if you keep changing the hole diameters locally, you can get multiple peaks as well. Now, so it is not all hunky-dory with the space-coiling metamaterials; obviously, you know, it is a recent technology, so there are some challenges and limitations as well, and currently, the noise control engineers and the researchers are focusing to try to overcome these challenges and limitations.

Challenges and Limitations

❑ **Fabrication Precision:**

- Issues with maintaining precision at small scales.
- Trade-offs between complexity and practicality in design.

❑ **Performance Limitations:**

- Limits on the types of waves that can be controlled using space coiling.
- Losses and inefficiencies that may occur in the real-world application.
- Lower value of SAC below 1000Hz.

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So, first of all, obviously, you know these are integrated structures. And the performance is highly sensitive to the geometry. So, this creates a lot of pressure on the manufacturing of these metamaterials. The manufacturing has to be perfect to get the exact kind of response. So, that precision is really important when you are fabricating or manufacturing the structures.

If you are not able to, you know, maintain the precision and the geometry, and due to some manufacturing defect, you know, there is a change in the structure or, you know, some bending or some internal defects which will, which is going to change your performance of the structure significantly. So, you have to maintain that geometry, and hence, manufacturing precision is required. In fact, there is always a trade-off between how complex your structure is and how practical it is to actually manufacture it. You can always propose a very complicated structure

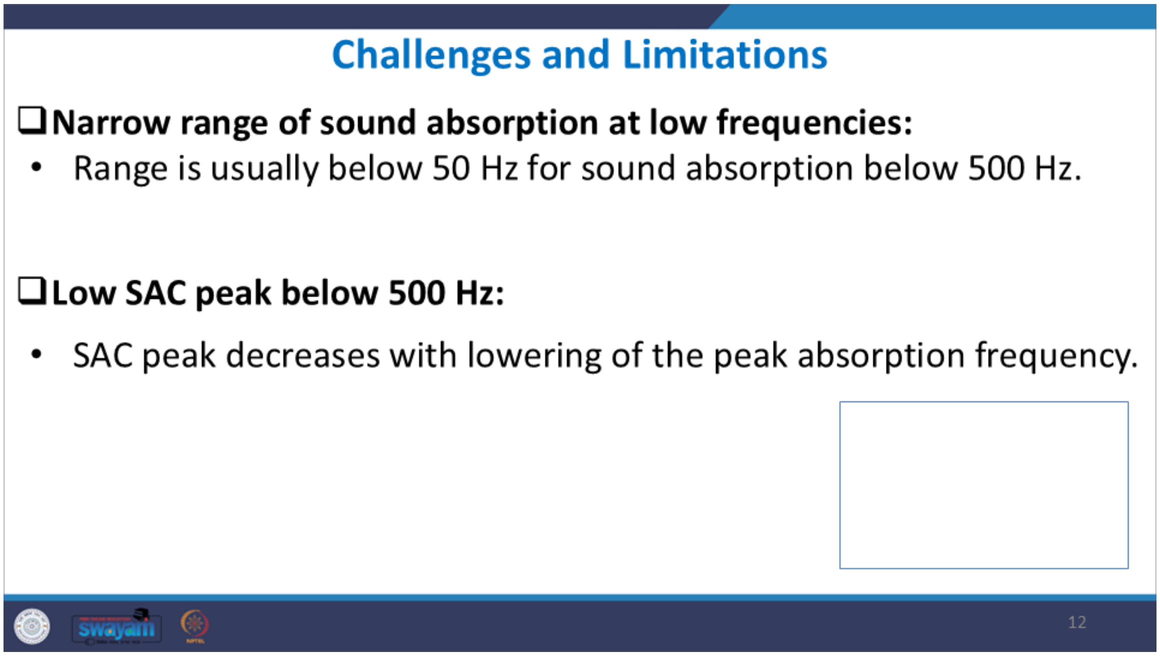
theoretically or, you know, as a concept, and it may be able to give you a very weird and new kind of sound absorption characteristics, but can it be translated into reality? Can you really, you know, use that complex design and create real-life structures? And not just that, because at the end of the day, these kinds of structures have to be used commercially in some machinery or mechanical systems, so they have to be manufactured in large sizes. in order to be scalable and commercialized. So, in that case, the structural integrity has to be maintained. There has to be reliability in the manufacturing of these structures. They have to be—all the samples that are being manufactured—they have to maintain the same overall, you know, quality of precision.

They also have to be manufactured in relatively lower time, and then the structural integrity should also be maintained at various kinds of temperatures in the presence of gases. and various kinds of atmospheres that the machinery might be subjected to. So, as a designer, you can always design a very complex structure, but it cannot be translated all the time into a practical solution.

So, there is always a trade-off, and that limits how much we can use this concept in a real-life appliance, okay. So, sometimes even if you propose a complex design, you might not end up using it in a real-life appliance. The other is, some of the other performance limitations are there. For example, you know, there are limits on the type of waves that can be manipulated because most of these are based on plane wave propagation. So, you know, the type of waves that can be controlled using space coiling is limited to that.

There are also some losses and inefficiencies that may occur when it is applied in real-world applications. So again, Compared to the other, you know, traditional noise control solutions or some of the previous noise control solutions, here the gap between theory and real-life application is wider. Okay. So, you can propose a lot of things in theory, but it may not really translate into a real-world appliance. So, that is a main challenge—you know, how to design something that can actually be made and commercialized. Then, in some of the lower frequencies, the SAC is still low.

It is not, you know, SAC is usually smaller than 0.8. There is, you know, a scope to slightly raise it up. Okay, one of the key challenges is the narrow band of sound absorption. And I think in all these lectures, what we have seen is that suppose we have got some resonance-type structure. So, in the resonance-type structure, the key limitation is that

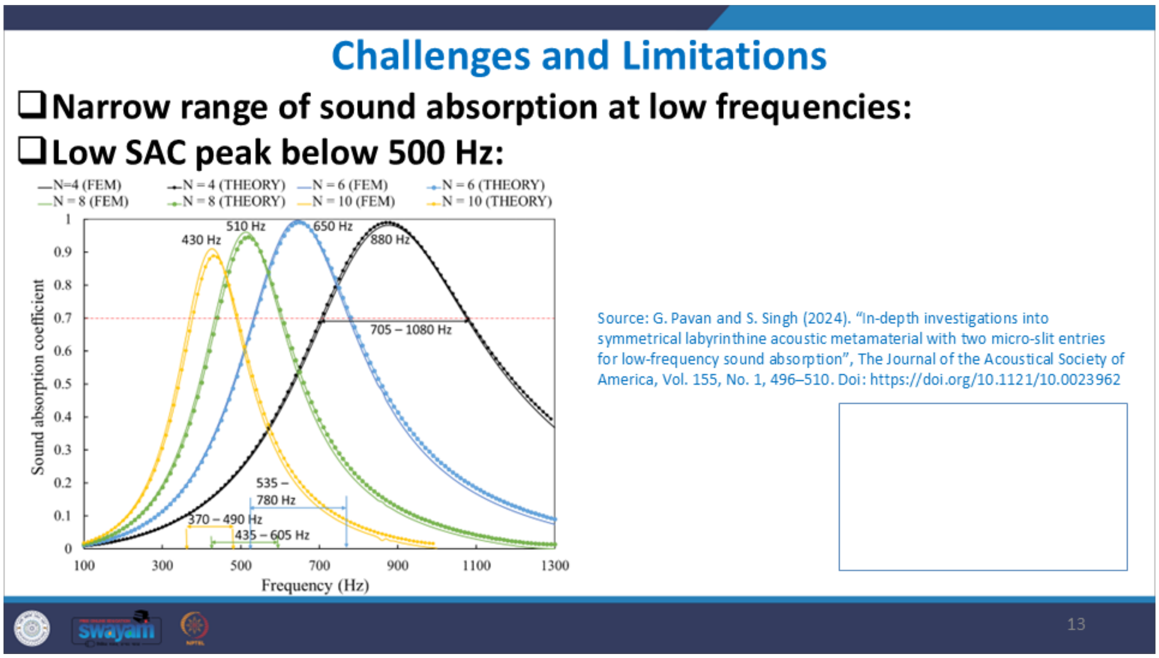


Resonance happens whenever the incident frequency matches with the fundamental frequency of the structure. So there is only a limited zone or a narrow zone over which resonance is happening. So if a structure is able to attenuate the sound only due to resonance phenomenon, then it will only have a very sharp peak. so usually you know you can have structures or you can have you know metamaterials or any kind of noise control structures where it should not be entirely dependent on the resonance phenomenon but there could be other effects as well for example viscous losses thermal losses, then frictional losses.

So, if other mechanisms are also coming into play, then they can be used to broaden the absorption curve. But if it is only resonance, it only happens pinpointed to a particular frequency and in that case, the range of absorption becomes very narrow. So, that is why other sound absorption mechanism that is the solution for it that the device or the noise control solution should not be entirely dependent on the resonance phenomenon. There should be other mechanisms also incorporated in order to attenuate the sound waves. For most of the practical designs you know suggested the range for the space coiling AMM or the range of sound absorption is below 50 Hertz.

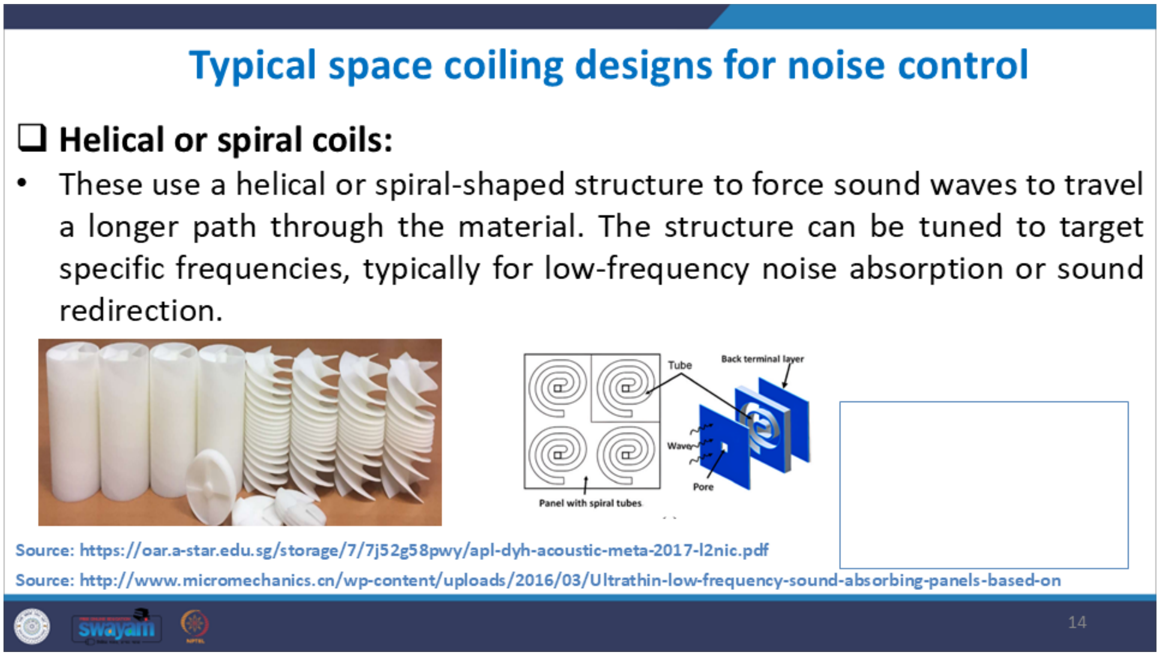
Typically this is just typically this is not always the case ok. So, I am not claiming this happens for all the designs right now there are many designs which are giving you much broader absorption, but typically like more than 80 percent of the designs existing are giving this kind of result ok. And how do you how are you measuring the range? So, here in this case I have considered the range where SAC is greater than equal to 0.8 as the range. Then again, low peak below 500 Hertz has been observed.

Let us see an example from one of our research studies to see if these two phenomena are happening. Again, this is the latest paper published by us in 2024. And what we see here is that, again, we are using the same metamaterial. The outside dimensions are exactly the same. Only within the inside are we increasing the number of folds.

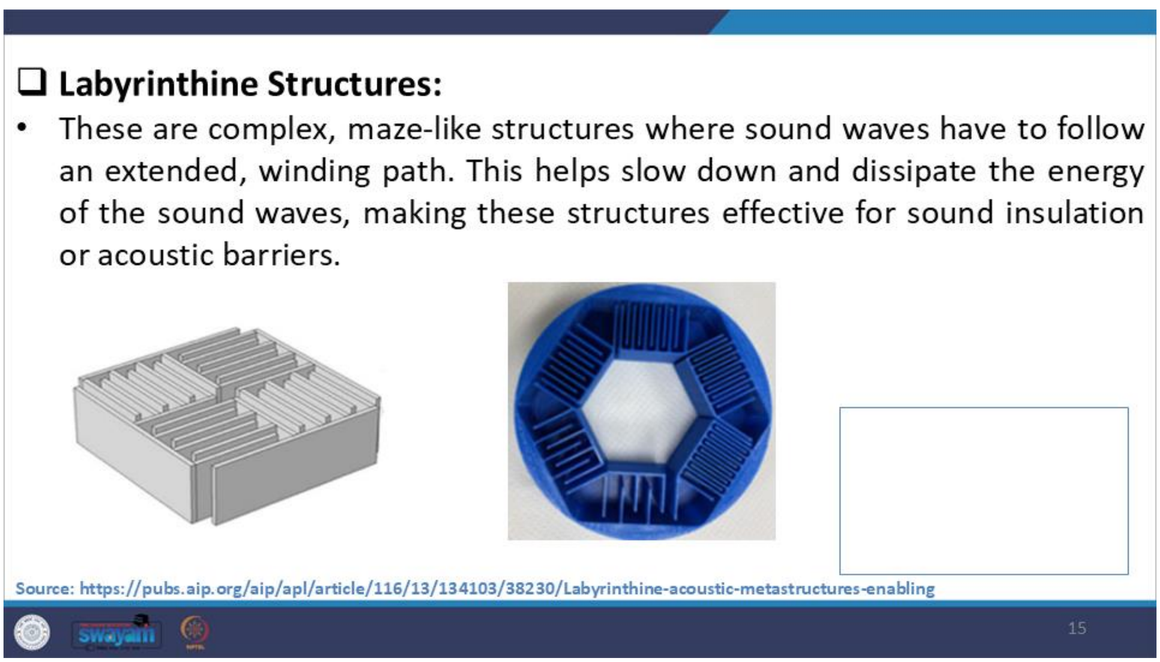


And as we increase the number of folds, The frequency of peak sound absorption shifts toward the lower end, but what you observe is that when the absorption response shifts toward the lower end, it also reduces the range over which the sound waves are absorbed. So, you have here a much broader curve, and then slowly the curve narrows down as it moves toward the lower frequency. And there is also a slight reduction in the absorption magnitude as it moves toward the lower frequency. So, this is generally observed for most space-coiling designs.

Now, let us see some of the typical space-coiling designs that are used for noise control. You have helical or spiral kinds of coil structures. So, helical structures, spiral coils, And they are tuned to target specific frequencies for low-frequency noise absorption, and the sound wave takes these elongated helical or spiral-shaped pathways.

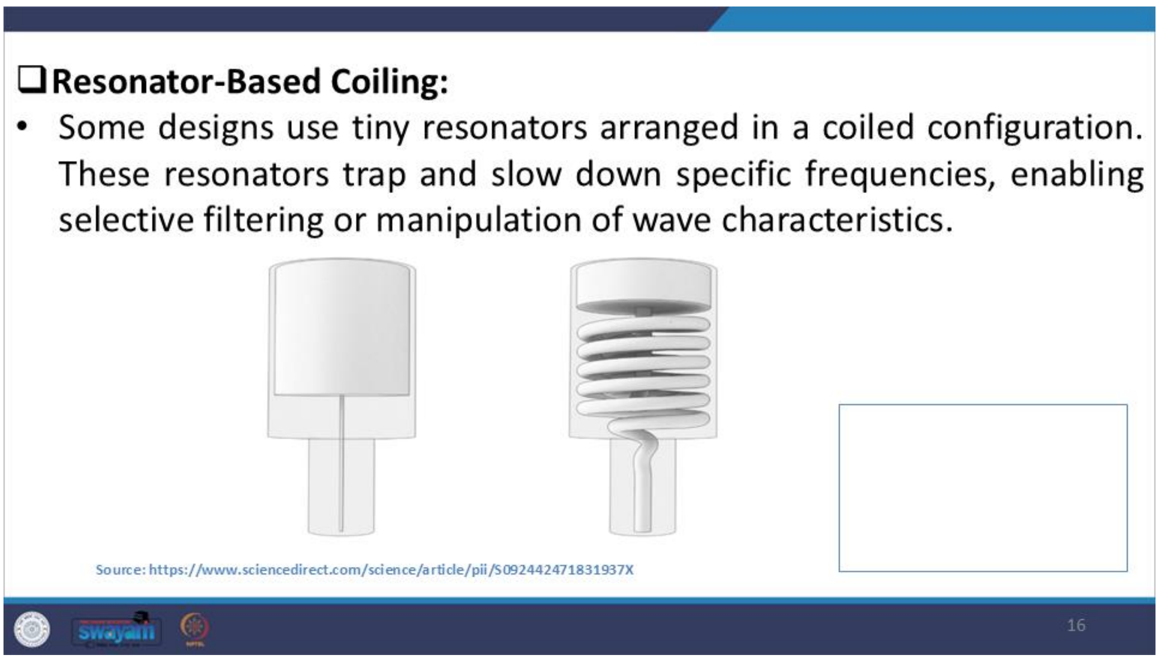


The others are these labyrinthine structures, and the research papers that we have published, which I was showing here, we have taken these kinds of labyrinthine designs where we do not have a spiral or a helical structure but rather straight turns, you know.

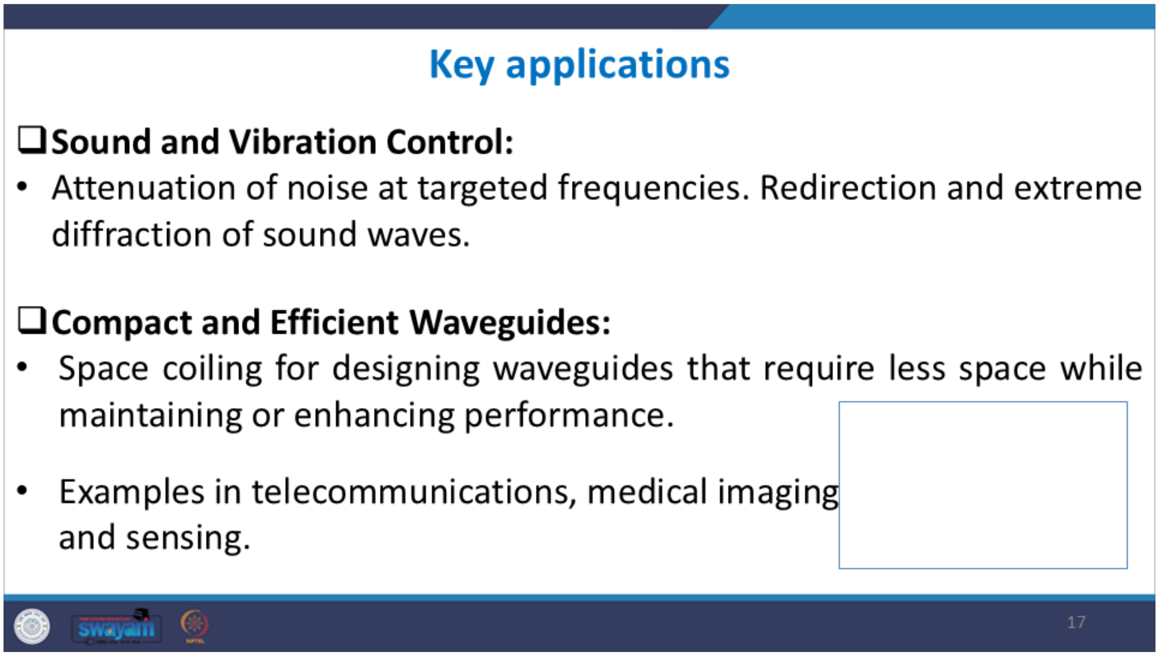


So, straight channels which alternately turn 180 degrees. So, these kinds of straight channel pathways or labyrinth maze-like pathways are easier to manufacture compared to these kinds of helical and spiral structures while providing similar sound absorption. So, that is why they are more commonly used in noise control applications. So, they have easier manufacturing compared to the helical and spiral designs, are simple in design, and perform similarly to the spherical and spiral designs, hence they are more widely used.

The straight channel pathways are more widely used. Then we have some resonator-based coiling as well, where you can have tiny resonating elements or, as you can see here, from the outside it looks like a Helmholtz resonator, but the sound wave enters and goes through these coil-like pathways, okay. Once again, there is complexity in design and manufacturing challenges with these structures, and the same goes here—complexity in design, and even though manufacturing challenges might not be present, the structural integrity is usually poor. It is poor, so it is difficult to maintain this structural integrity in harsh environments. Okay.



So, now let us see the key applications of these space-coiling metamaterials. So, firstly, obviously, because our lecture series is on noise control in mechanical systems. So, we are only studying noise control applications. So, here the very first application is definitely sound and vibration control. So, these space-coiling structures can not only be used to control sound waves but also to attenuate vibrations through them.

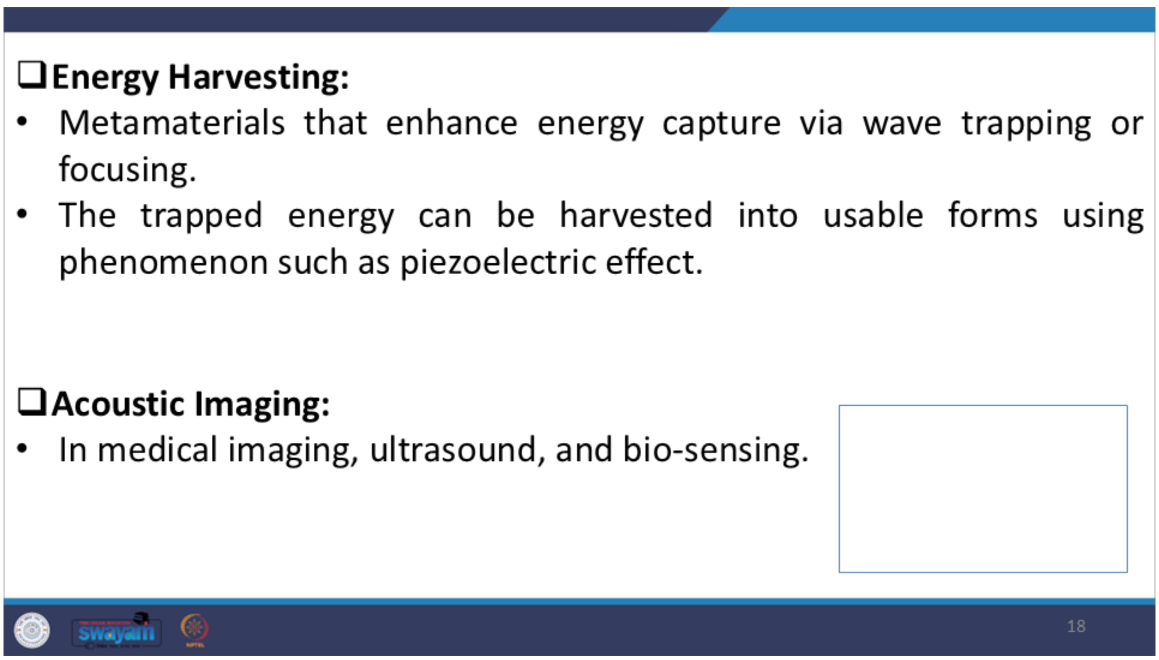


And the designs for the two are different. So, any kind of elastic wave—whether it is a longitudinal sound wave passing or a flexural vibration wave passing—these kinds of space-coiling structures can be used to target and redirect these waves, hence attenuating them while they travel along these structures. Then, some other applications beyond noise control are that you can make compact and efficient waveguides. What is a waveguide? Just like we have an optical waveguide, we have an acoustic waveguide.

So, what is an acoustic waveguide? It is, you know, a structure used to direct the sound waves—the structure that is used to direct the sound waves in some intended pathways. For example, I will refer to the example of optics where we had these optical fibers. We have these optical fibers where concentrated light waves can pass through these cables and can be redirected in any pathway we like.

In the same way, they can be used as acoustic waveguides to concentrate the sound waves and redirect them throughout the structure in any format you want. So, for example, you can have a waveguide that can redirect the sound waves. So that it travels and can be transmitted over long distances by redirecting these sound waves along these intended pathways, okay, like that. So, just like optical fibers, they are used for, you know, imaging and communications. They have been used—fiber optics has been used for communications, telecommunications, and imaging. In the same way, instead of just using light waves, we can use waveguides or some kind of structure that can be used efficiently used.

To direct and make the sound waves travel in a concentrated form over long distances with very little loss, and we can just redirect and make them travel through long intended pathways without significant losses, then they can also be used just like fiber optics. They can be used for telecommunications, medical imaging, sensing, etc. Energy harvesting is a relatively new concept where these metamaterials are showing potential. There is not a practically available solution yet, but theoretically and numerically, concepts have evolved which demonstrate that these metamaterials can enhance energy capture. How can they be used to trap it? The and focus the sound waves and convert them into usable forms using the piezoelectric effect.



So, what happens is that we can, just like they can be used to create acoustic waveguides, we can have some space-coiling structure, let us say, which can be used to Some kind of space-coiling structure can be built which can be used to direct and focus the sound waves in a localized region. So, let us say all the sound waves incident are getting focused into some localized regions. Ok. So, this vast amount of sound waves is now getting concentrated and localized into this small region, and then we can have some piezoelectric phenomenon or piezoelectric material.

So, the large amount of sound waves is now getting concentrated into a small zone, which is increasing. So, here the acoustic energy has increased a lot. So, the vibrations or the amplitude of vibrations of the particles have increased manifold and are then getting converted by the piezoelectric effect. So, you can have a certain membrane-like structure.

The sound waves, the concentrated sound waves. So, here you have the concentrated sound waves, which are incident on a membrane-like membrane, and then they pass through a piezoelectric kind of patch, okay? So, what is essentially happening here is that the phenomenon is something like this. I will just draw a flowchart for this. What is happening? Incident sound waves first use the SCM; they are incident on the SCM structure, the space-coiling structure or a metamaterial, and this leads to, you know, redirection and focusing of the waves.

In small localized regions, and then the energy is trapped—high energy, high acoustic energy—is trapped, which is incident on the membrane and leads to very high membrane vibrations. And then, you know, the piezoelectric patch converts high vibrations into electricity. So, this is just, you know, a basic kind of schematic of how, you know, energy harvesting happens. You trap the sound waves and focus them. In localized, small, confined regions, and in those regions, we have high acoustic energy.

Trapped within these small regions, and there is a light membrane on that region. These high-intensity waves are incident on that membrane; they vibrate the membrane. So, the membrane starts vibrating heavily, and then there is a piezoelectric patch attached at the other end of the membrane. So, these large vibrations of the membrane Drive the piezoelectric material, and these vibrations get converted into electricity by the piezoelectric effect.

In the same way, just like fiber optics, acoustic imaging can also work similarly. If we can redirect and focus the sound waves, we can achieve good imaging in medical fields, such as ultrasounds and biosensing. These kinds of applications can be used. Okay, so with this, I would like to close this lecture. Thank you for listening.

Thank You