Biomedical Ultrasound: Fundamentals of Imaging and Micromachined Transducers

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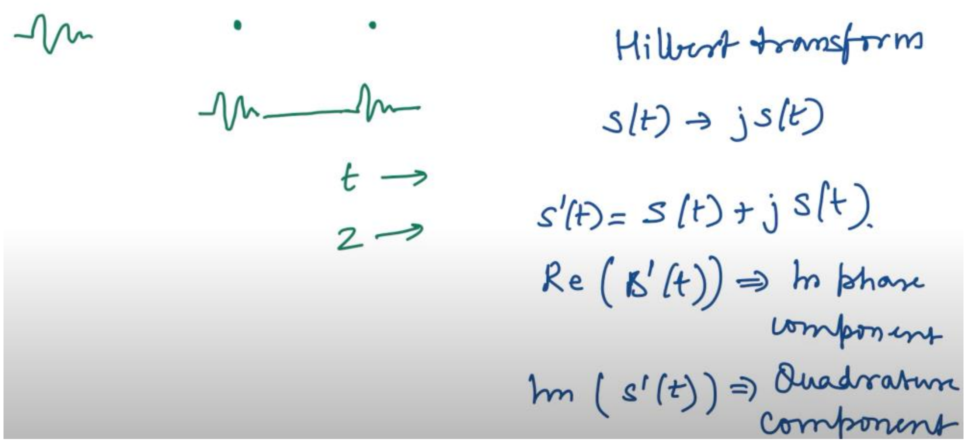
Lecture: 35

Recap of week 7

Hello and welcome to this lecture. We will revise the topics that we discussed last week along with a few additional topics. So, you'll recall we talked about envelope detection very briefly. We said that if we have, let's say a target and we send an ultrasound pulse like this, then after a delay, you will receive a signal like this, right? Now, what this tells us that at this location in time, and I can convert from time to space by using the speed of sound. So, it tells us that at a particular instant in time or at a particular location in space, there exists a signal and there is another one after a certain delay, which means that there are two scatterers that have located one distal to the other. Now we would like to locate the position of the scatterer.

We are not interested in these high frequency oscillations that are going on here, which is essentially like the carrier frequency, which is the center frequency of the transducer. So, this is akin to modulation. You may have heard of amplitude modulation in which there is a carrier signal, and the message signal rides on top of it. Similarly, we are trying to locate the scatterer.

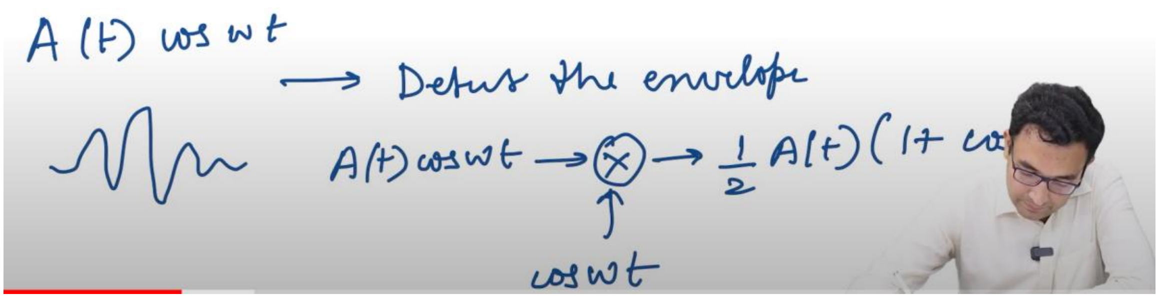


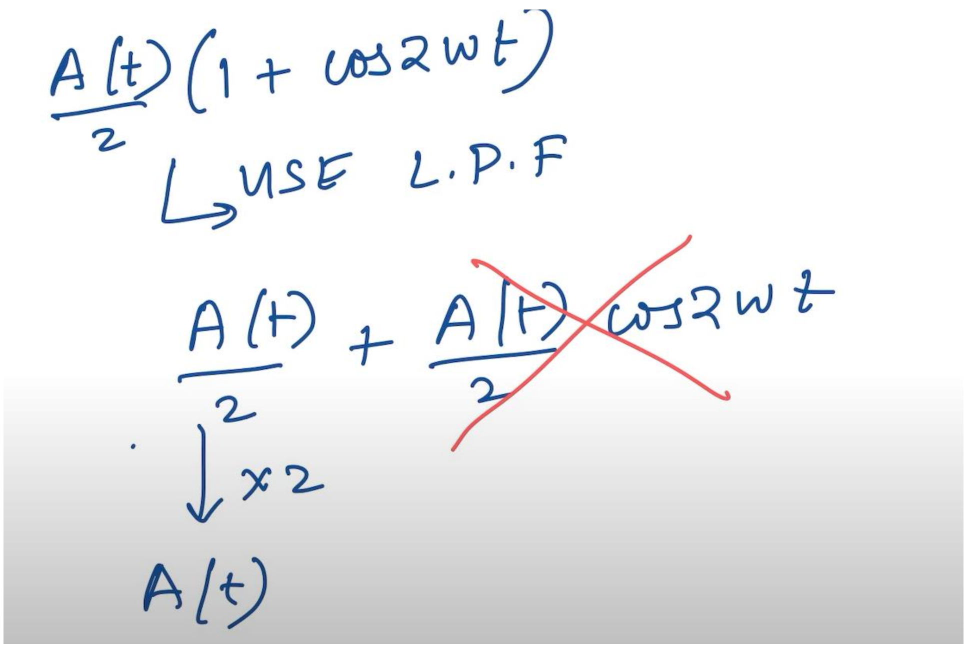
So therefore, we would like to just take the envelope and to take the envelope, this can be done by the Hilbert transform. So, Hilbert transform essentially performs a phase shifting operation. If you have ST, you can get J times ST, and this helps us create the analytic signal. So, you may be aware of the analytic version of a real signal which can be created as st plus j times st. Now this has real and imaginary part with the imaginary part being phase shifted by 90 degrees with respect to the real part.

Now the real part is called the, so if we call it analytical signal as s prime t, so real part of s prime t is called in-phase component and the imaginary part is called the quadrature component. Now, by using the absolute value of the Hilbert transform. You can actually do this function in MATLAB, and this will give you the envelope. It gets rid of the carrier frequency. But now, as it turns out, Hilbert transform is great when you have like a GPU or a CPU. You're essentially doing this operation where you have the numbers already and you are doing this operation either using a GPU or CPU.

But when you need to detect an envelope, using hardware. Now this phase shifting operation phase shifting exactly by 90 degrees is challenging when it comes to hardware. So, for example you may have an ASIC chip application specific integrated circuit. That's where this phase shifting is a challenging operation. So, in practice what is done is slightly different.

So, imagine if you have a signal which is given by AT cos omega t. This could be a signal with this type of profile where the amplitude is also a function of time and then you have a cos omega t function. So, what we would like to do is detect the envelope A of t. So, from this we would like to detect the envelope. And for this, what we would like to do is use a very simple process.





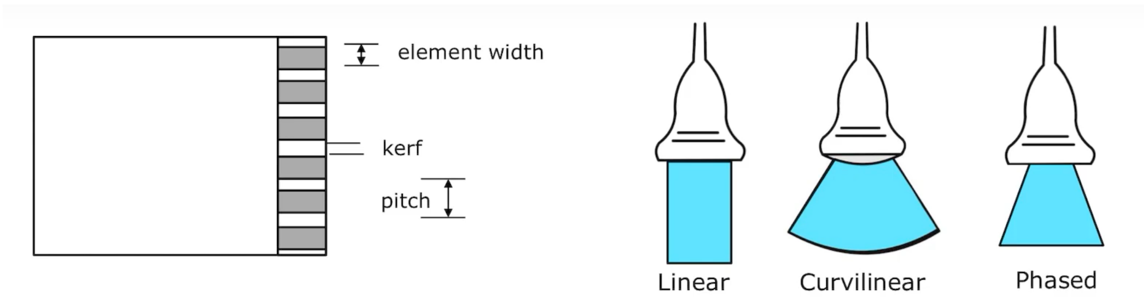
We are going to multiply this with another function. So, what we are going to do is we take this a t cos omega t and we multiply it with another function which is also cos omega t. So, you know the frequency that was transmitted using that same frequency when you do the multiplication you get a product of cosine and using your 11th grade trigonometry this can be written as half of A(t), 1 plus cos 2 omega t. So, if we take this expression, you can see that the first term is A(t) by 2. So essentially if we give a gain of 2, then we will recover the envelope and the second expression is A(t) multiplied by a higher frequency signal, right? 2 omegas.

So, what we can do is we can use a low pass filter and by using a low pass filter, of appropriate frequency, we can get rid of this high frequency term. And if we provide a gain of two, so you just multiply the times two, you get back the envelope signal. So, this is a practical way in which it's done very frequently. And there are also some advanced techniques. For example, if there is a slight phase difference, for example, here, when we are multiplying them, if there is a slight phase difference that can cause some extra oscillation, there are some clever tricks that signal processing engineers have designed to get rid of those two.

So essentially, this is how you can get the envelope. Once you have the envelope, you can log compress the signal and you can reconstruct your image. Okay, so now after covering that topic, let's come to the recap.

So, we discussed different types of transducer arrays in the preceding lecture. If you remember the construction of a transducer, there are these elements which are rectangular in shape.

Why does the shape have to be rectangular? Well, this helps with elevational focusing. That's why they go for a rectangular and not spherical shaped element. And it has a certain element with, there'll be some insulating layer between these elements to prevent shorting of these transducers. and the element-to-element distance. So, if I go from the center of one element to the center of the other element, it's called pitch.

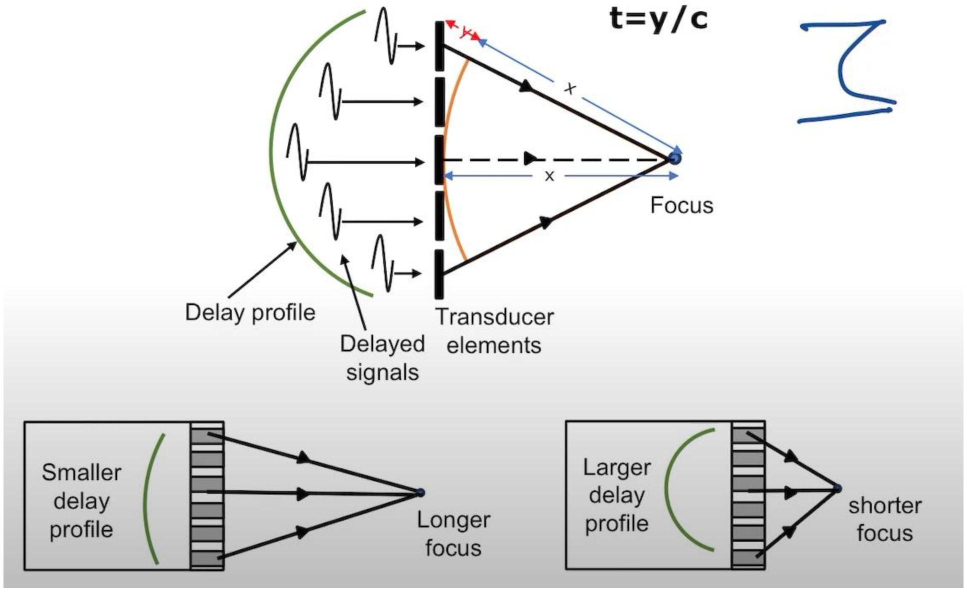


If you do simulations in field two, you will need to know these factors for your transducer. These parameters are essentially what they are for the transducers that you are trying to simulate. And then the three common types of arrays.

There are other types of arrays. For example, there can be 1.5D arrays, matrix arrays, etc. But these are the most common types of arrays. And typically, we choose the number of elements in the array.

For example, here it is 1, 2, 3, 4, 5, 6. Well, it turns out this is just an illustration, it is 6. But typically, you would go for powers of 2 like 8, 16, 32, And in advanced arrays, typically you would see 64 or higher number of crystal elements. Now, when these elements are fired, they approximately create a spherical wave and then they can be electronically scanned to obtain B-mode images in different ways. You can fire them all together, which is called plane wave transmission.

You can do focus transmissions, or you can do what is called a synthetic aperture transmission. So, we discussed how to focus, right? We have said before that if it's a single element transducer to focus, you would need to have a concave geometry. So, a concave geometry like this, which will enable focusing naturally, right? Or you would need to have a kind of lens. So, let's say if my transducer is like this, I can place a lens in front of it. and this lens being concave will help me focus.



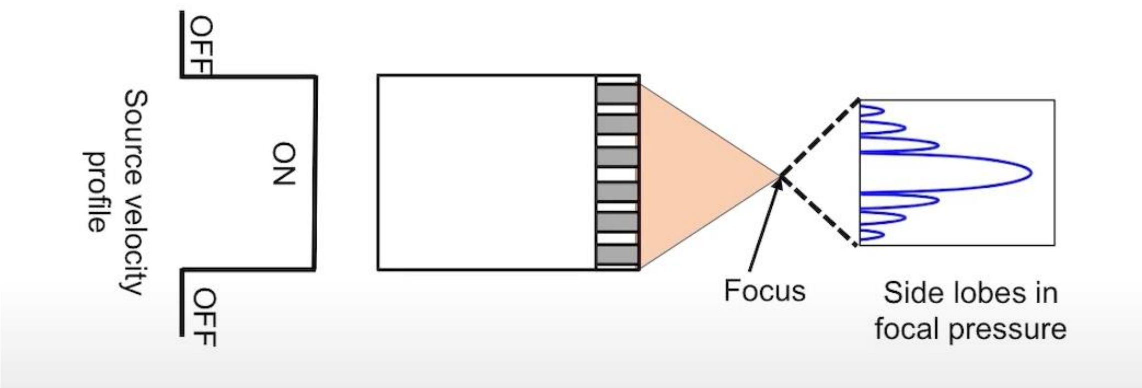
So, this is what you do when you have a single element transducer. But when you have an array transducer, what you can do is you can provide different delays. And here is an illustration. While if you want the constructive interference to happen at the focal point, what you need to ensure is signals from all the elements should arrive in phase and that's going to happen when you compensate for the change in path length. For example, from here to hear the path length is shorter, from here to hear the path length is longer.

So, if you compensate for that extra path length by providing a delay to the element which is actually closest to the focal zone, that's when you are able to create this delay profile. So, what this means is this element and this element receives the excitation first, it fires first, and the center element receives the excitation last. So, it fires later, but essentially all these waves arrive together in focus. And here is an example how we can also change the focal length within certain limitations of the size of the aperture, number of available elements, etc. We can change the depth of focus.

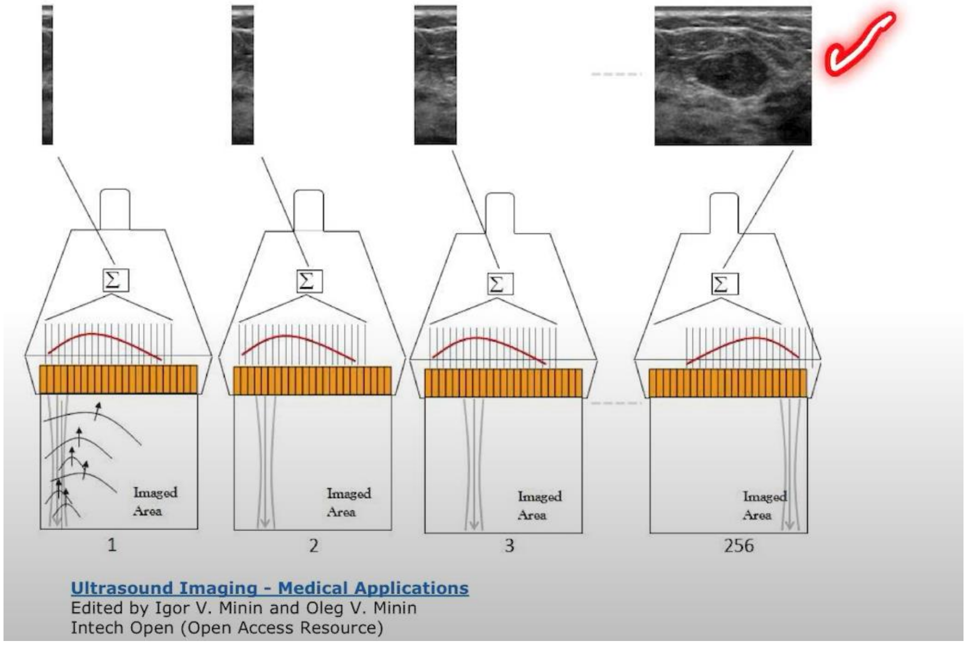
For example, if I choose a delay profile, which is like this, then I can go for a longer focus. but I can have a sharper delay profile and go for a shorter focus. So, these are some possibilities when you have an array element. We also discussed apodization in some detail. We said that apodization or essentially foot shaping enables us to form a smooth beam, right? What do I mean by a smooth beam? Well, if a beam does not have a lot of side lobes, that would be a smooth beam and the reason why we need to go for this apodization is because the pressure field at the focus has a Fourier transform relationship with the source velocity.

And the source velocity typically simply mirrors the aperture function. So, if the shape of an aperture function is like a rect, then the Fourier transform will indicate a pressure profile that resembles a sinc function. And you know sinc function has high side lobes relative to the main lobe. So, to get rid of the side lobe, we can provide an apodization function and that will reduce the side lobes that are formed and that will improve the contrast resolution. But we also discussed that nothing comes for free.

So, what you gain in contrast resolution, you have to sacrifice something in terms of broadening of the main lobe that will reduce the lateral resolution. Also, as you produce this profile, you are in a way sub optimally using some of these elements because they will be firing with low pressure. So, even the signal to noise ratio and the penetration depth will be reduced when you go for apodization. And here are some examples that we had seen, like if you have a rectangular window or the aperture or the source velocity function. resembles a rectangular window, then you get the Fourier transform here with a very high side lobe level.

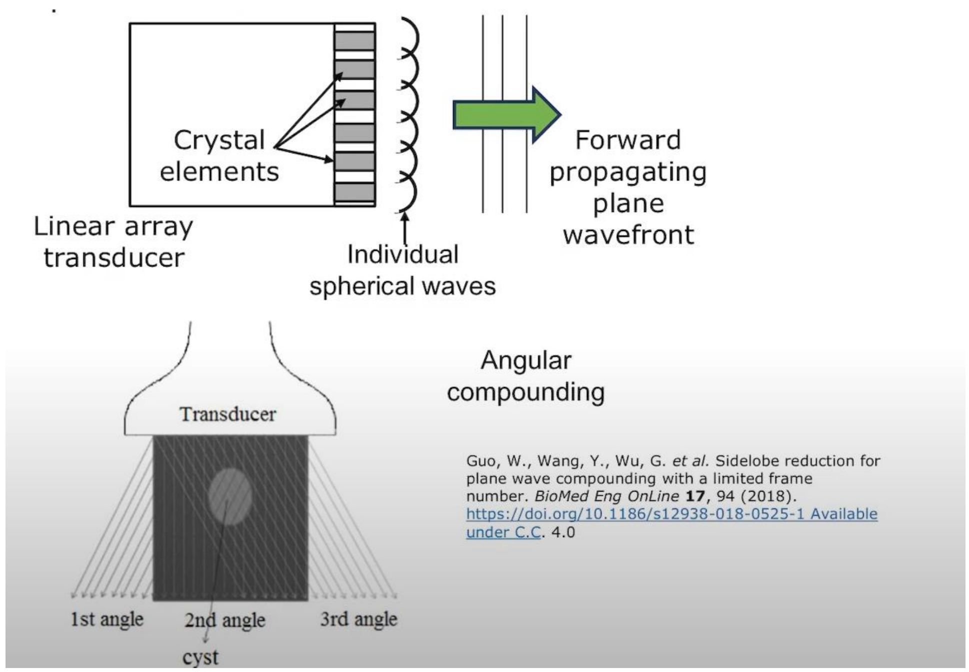


But if we provide Hann window, so Hann is a smooth window function, then you can see the side lobe level has dipped considerably. But you also see that the main lobe here is not as sharp as this. So that's what signal processing is. It is essentially about trade off. So, then we discuss the types of transmission mode which are plane wave transmission, focus transmission, synthetic aperture transmission etc. So, in linear array imaging, now even though we are imaging with a linear array but typically the standard way of doing it is the focus transmission mode and typically we also call it linear array imaging. Here what we do is we group a few elements and fire them to get an A line and once an A line is formed, so this represents a single A line and when we keep shifting and stacking up the A-lines together, eventually we will create an image. And we want to create a focused beam. So, when we focus on the beam, at least at the focal point, you will get good lateral resolution.



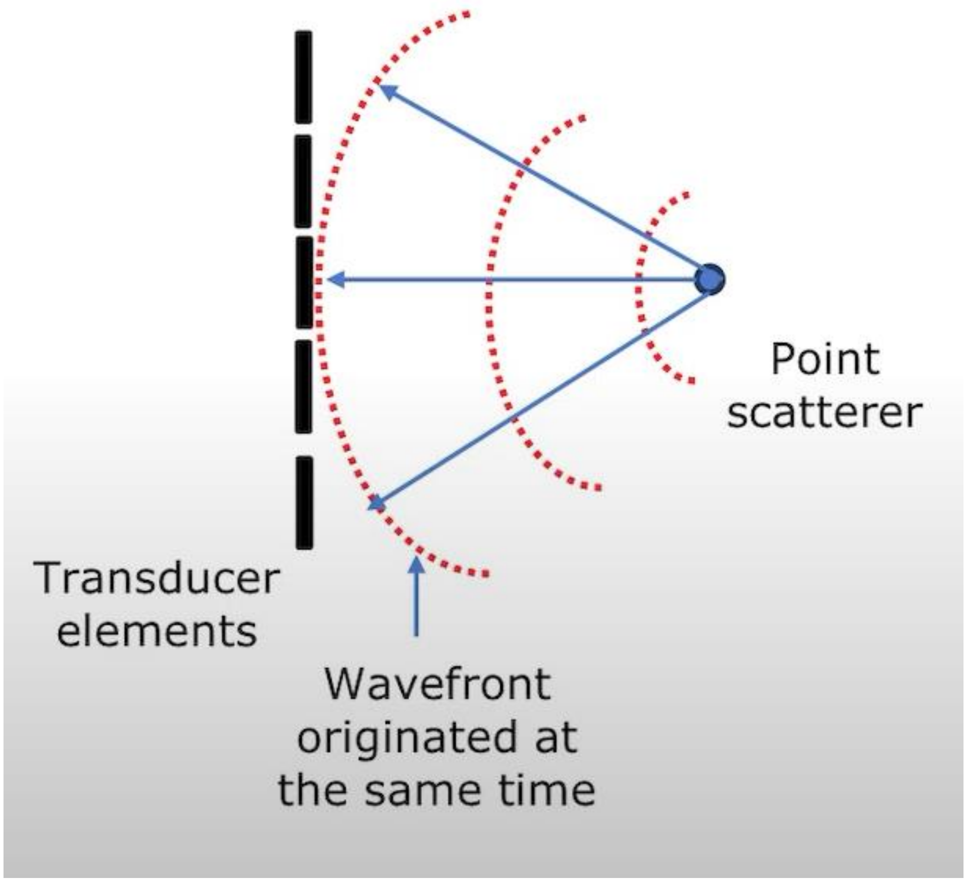
And as you are shifting laterally, that focus is also shifting.

Now we discussed ultra-fast imaging. And ultra-fast imaging is used when you want to visualize fast-moving phenomena. Examples can be opening and closing of valves, although they are not that fast they can also be visualized at real time frame rate let's say around 80 frames per second but there are certain phenomena for example propagation of shear waves in the body which requires ultrafast imaging with frame rates that can range from several hundreds to thousands of hertz so in ultra-fast imaging you fire all the elements together and therefore you create a plane wave front so here all the elements they are fired together, the signals interfere and you get an approximately plain wavefront and then this produces poor lateral resolution because there is no focusing here. So, one way to improve the lateral resolution is to go for angular compounding in which you fire at certain angles, and you essentially sum up the signal together which is called compounding.



This helps improve the resolution but of course it will also reduce the frame rate because instead of creating a single image if you are taking data for say five images or three images, where you're firing at five angles or three angles, then the frame rate will reduce by the same factor.

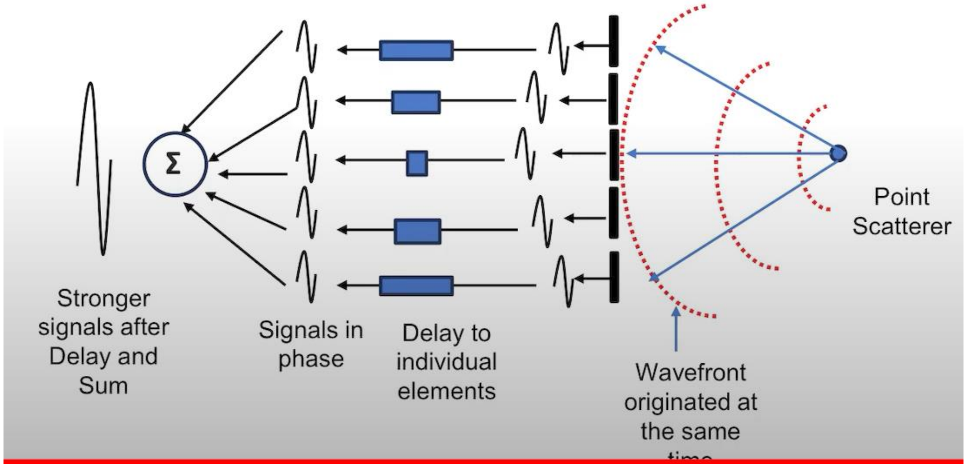
Now beamforming is not only in transmit, but in the receive mode also, when the signals are coming back from the scatter also, you can employ beamforming to improve your imaging performance. So, when we take the signal from a point scatterer, let's assume that this is scattering like a Rayleigh scatterer, then the signal will travel spherically, almost spherically and reach all the elements at different time points. So now if we simply sum these signals, then they are not going to sum in phase. So again, it's important to correct for the time of flight so that all the signals sum in phase and you get a strong signal representing the scatterer.



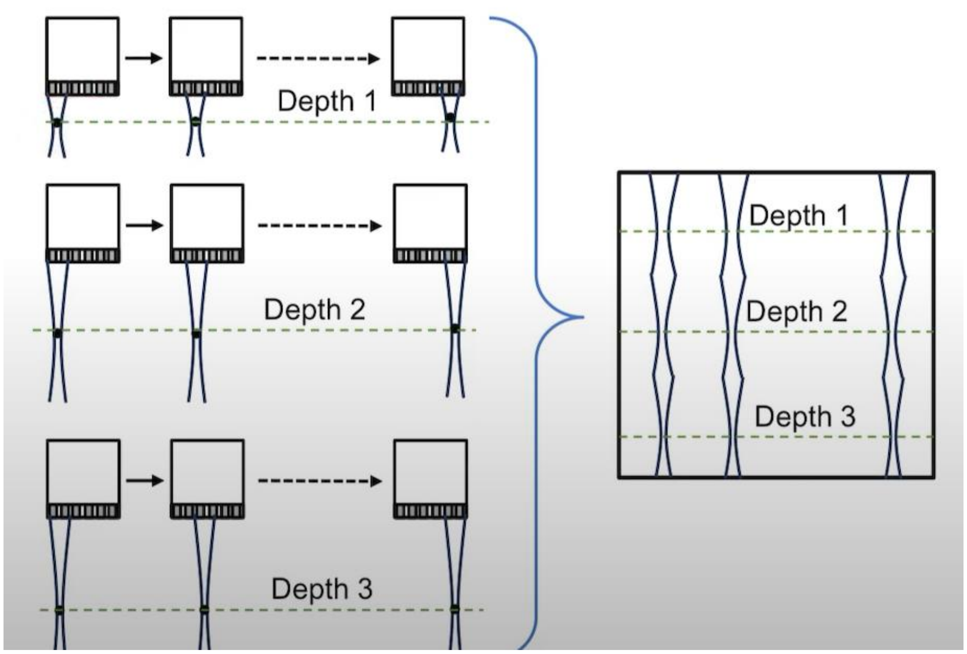
And essentially you will get the point spread function of the scatterer if it is a sub-wavelength scatterer. Now, if you don't do this process, right, then the scatterer will appear somewhat stretched, elongated like this in your image, pre-beamforming. But after beamforming, you will be able to recover the scatterer to the extent possible by your point spread function. We discussed the most basic beamforming in the last lecture also. Pen and paper, we discussed the delay and some beamforming, just jogging your memory here.

We said that because the signals have to be added in phase. There has to be some way through which the signals will be time compensated. And the simplest way is to use geometry, and we assume a standard speed of sound for soft tissue, which is an average essentially of 1540 meters per second. Using that and using essential geometry, we provide different delays. We bring the signals in phase, and we add them, right? So, once we take these initially incoherent signals and we bring them in phase, then we combine them to get exact spatial distribution of the object.

I mean the word exact would not be appropriate because it would be limited by the point spread function of the system. But nonetheless that is as close as we can get. So this is the most standard beamforming approach and you can also look up other advanced beamforming topics. This is an area of active research being performed in the community.



A couple of topics we have discussed already including DMAS beamforming which is delay multiply and sum beamforming and also we discussed coherence factor, we discussed minimum variance distortion less beamforming etc. in some brief. I think you can look it up further. Now let's discuss dynamic focusing. Now dynamic focusing can be done in transmit as well as in receive.

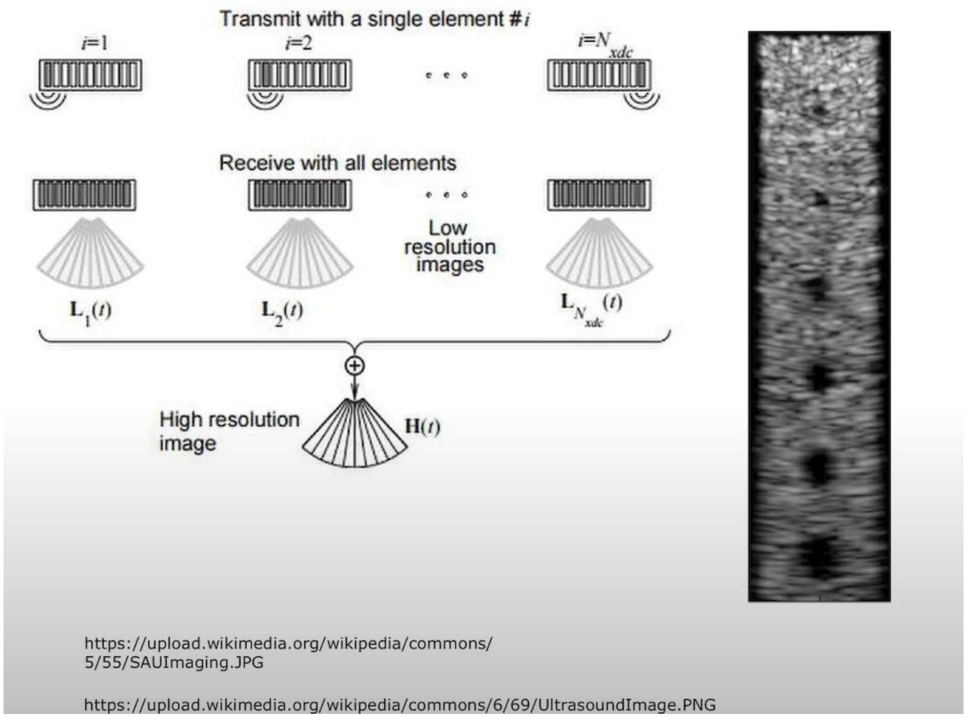


Now in linear arrays, the best lateral resolution that you can get will be at a particular depth. So, for example, let's say I provide a delay profile which enables me to focus on a particular axial depth. So, this is the depth at which my lateral resolution will be best, and it will be poor at other depth because of diffraction and beam divergence. But if I do a process called compounding wherein I first focus at a particular axial depth and perform the imaging then I change the depth by changing the delay profile and then I acquire the data and then I further change the depth and essentially I combine those three then what I can do is I can form an image with three foci and because of which the lateral resolution is not degraded in the image substantially. Now this is a technique of dynamic focusing but the challenge here is it affects your frame rate because you have to fire again and again at different depths.

So, this is used but not so commonly. But there's also the technique of dynamic focusing on receive. And in this case, once you have the data, you can artificially in the computational domain, you can adjust the receive focus. You can essentially create a grid. And if you are reconstructing any point or any pixel in that grid, then you can calculate the time of flight from that pixel, align all the signals in phase, and then you can sum them up. So essentially you are performing this process of dynamic focusing on receive where each pixel is actually focused by this process.

So, when you do this, the beam width is minimum at multiple axial depth and thus the lateral resolution is enhanced. Of course, all these techniques will need some additional computational resources, but you get a better imaging quality. We also discussed synthetic aperture imaging, and we discussed that typically you don't have a large aperture because of hardware limitation. So, what you could do is artificially synthesize this large aperture by moving a small active aperture over a large array. And then later when you have the data, what you have is essentially a full matrix of transmit and receive.

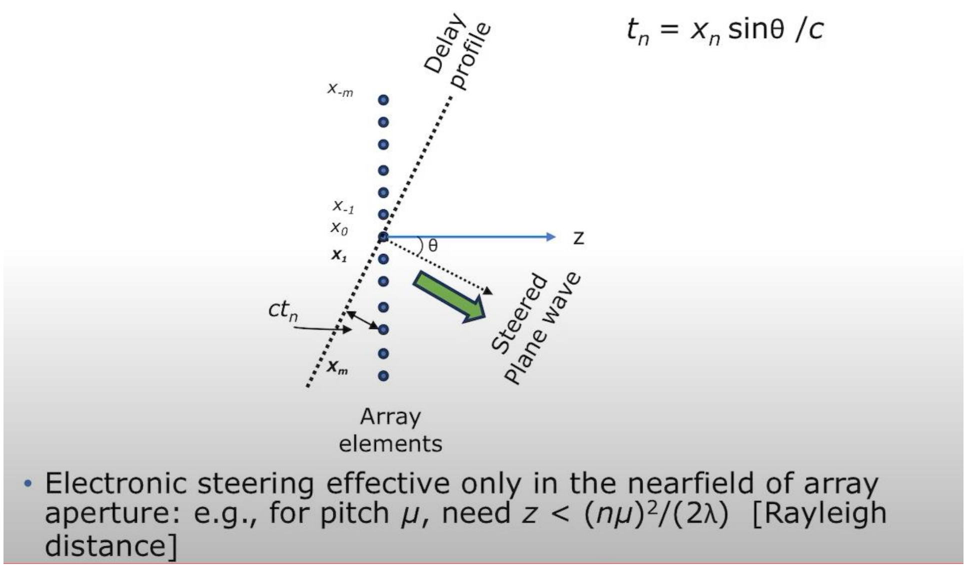
From that you can create high resolution images. So here is the illustration. where you are firing with one element, but you are receiving with all elements, and you keep shifting that element from which you are firing and then you keep receiving with all the elements. So essentially now you have the complete data set and from that where each firing will typically give you one low resolution image, when you fire as many number of times as there are elements in the array and you sum up the signal, you get a high-resolution image which is a synthetic aperture image. But this is a slow technique and data intensive technique. Therefore, it's used only in some specialized applications.



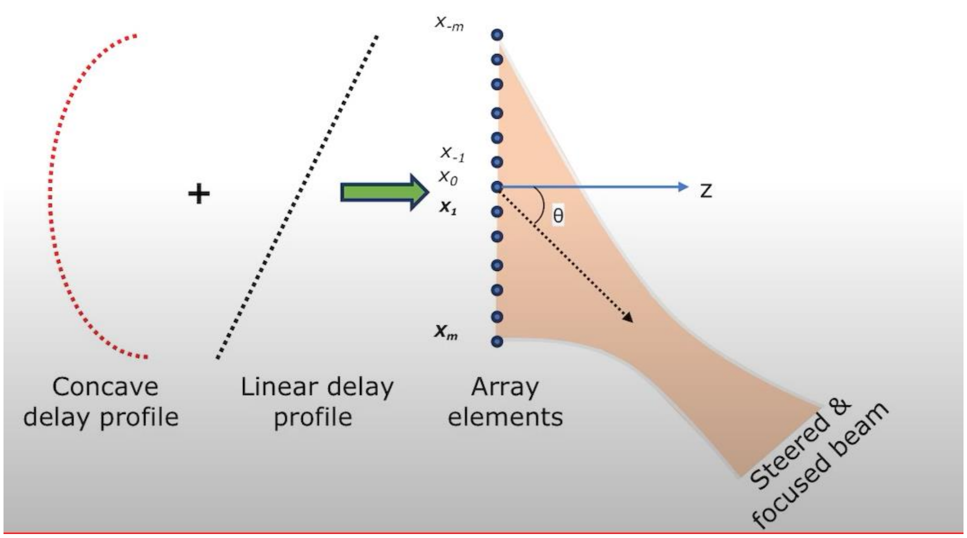
Then we discussed the robust skip on beamforming, if you remember, which is also known as minimum variance distortion less response beamforming. And the word robust is because it employs some optimization techniques so that it is robust to some differences arising from practical issues such as noise, differences in sensitivity of transducer elements, difference in positional accuracy of transducer elements, etc. So, what this technique does is that it essentially penalizes the power beyond the axis. So, it tries to reconstruct in such a way that the power of the signal from a desired direction is maximized and from other directions is reduced. And for doing this, the weights are actually adaptively adjusted for each array element.

And because of this, you know, you get a better imaging performance when you go for robust keep on beamforming. But this is highly computationally intensive. It requires some linear algebra, which is computationally intensive. And therefore, it is used again in more specialized applications.

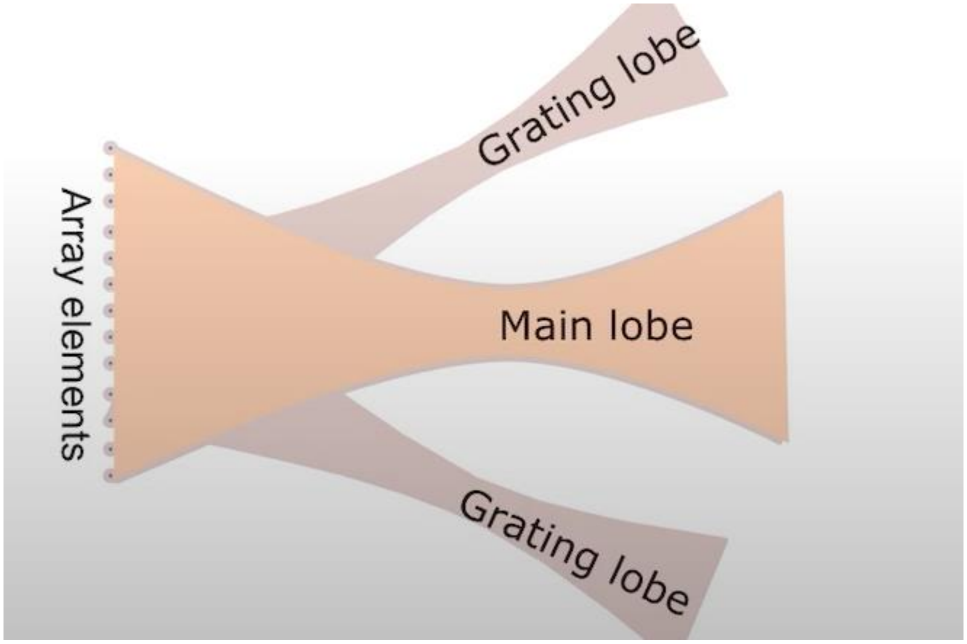
We discussed beam steering. what delays we can provide so that you can beam steer in a particular angle. Even in the last class we discussed this in some detail, and we also discussed that this steering actually is effective more in the near field. In the far field this is not so effective. We discussed how we can go for both beam steering and focusing. So, if you think of focusing as providing a concave delay profile and then a linear delay profile for beam steering.



If you combine those two delays and you provide them at once, then you will get a steered and focused beam, and this can improve with targets which are hidden behind small acoustic windows. So, through this small acoustic window, you can look at a wider field of view with good lateral resolution because now you are combining beam steering with focusing.

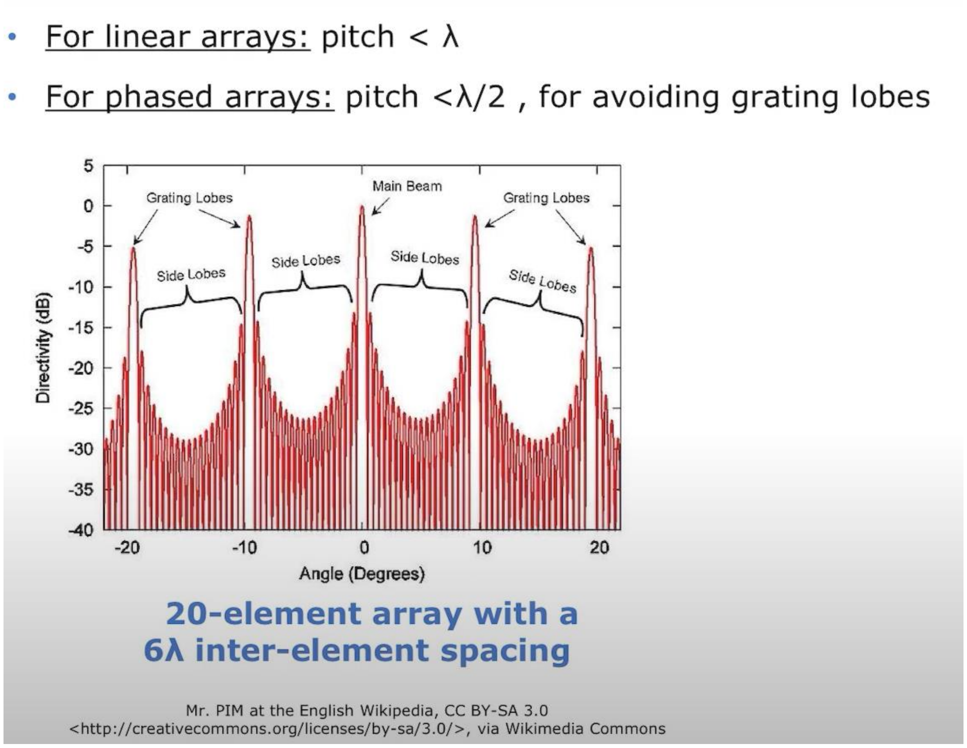


We also discussed side lobes. If you remember apodization, we discussed side lobes, spatial side lobes, which are poor for the contrast resolution of the image. But there are also additional side lobes in array signal processing called grating lobes.

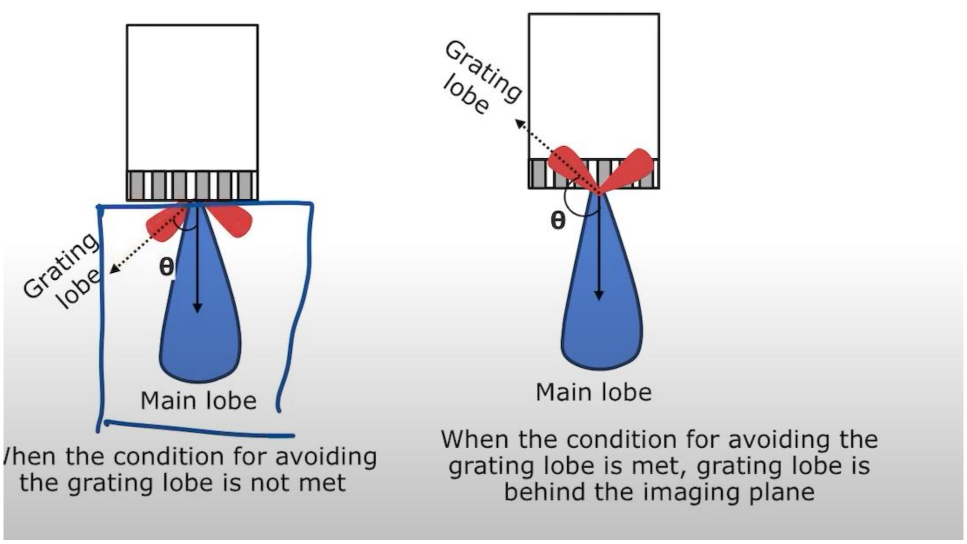


And these grating lobes arise from spatial under sampling. So, for example, if you have transducers with a certain pitch, and you are trying to do beam steering. And if this pitch is not appropriate, then you will get these grating lobes because of this condition where the constructive interference happens not only in the direction of the main lobe, but at these angles also where sine theta equal to n lambda by mu. So, especially for higher frequencies, when imaging is performed at higher frequencies, for example, let's say 15 megahertz instead of 2 megahertz. These problems become quite persistent. So, these grating lobes are something we would like to avoid and suppress. And here is the condition that needs to be met to avoid grating lobes.

If you are using a linear array, then the pitch needs to be less than the wavelength. So, sub-wavelength pitch. And when you are using a phased array, where you will be doing steering, So, by the way phased array is also like a linear array, but it is special in the sense that the pitch has to be less than lambda by 2 which allows you to do beam steering as well without grating lobe. So here is an illustration where there is a main lobe, and this is a function of angle by the way. So, as you can see there is a main lobe present at 0 degree but some strong grating lobes which are almost comparable only about 5 decibels or 3 decibels lower than the main lobe are also apparent in this case at some angles of 10 degrees and 20 degrees. So, we would like to avoid this because this array had a 6 lambda inter element spacing. Instead of lambda by 2 or less, this had a 6 lambda inter element spacing. So, these strong grating lobes are inevitable. Now what happens if you fulfill this criterion with a linear array of having at least lambda or rather at most lambda spacing and for a phased array having element smaller than the size of lambda by two. If you do that, the condition that sine theta equal to n lambda by mu still holds, but now the grating loads don't appear in your region of interest.



So, for example, if this is my region of interest, then in the first case where you are violating this criterion, The angles at which the grating lobes appear are such that they actively interfere with your image. So, they appear in your image very strongly. But when you have the proper pitch, for example, mu less than lambda by 2, then these grating lobes actually face in the backward direction, and they do not interfere with the region of interest where you are performing the imaging. So, this is how you are able to avoid these strong grating lobes by fulfilling these criteria.



So, let's summarize this lecture and I hope this review has been useful to you.

So, we discussed the topic of envelope detection, we discussed how focusing can be performed in array transducers by providing delays and by changing delays we can also change the depth at which you are performing the focusing. We discussed again the different transmission modes; plane wave synthetic aperture imaging and focus transmit imaging. And we also discuss how beamforming is performed for all of these. And lastly, we discuss both the transmit and receive aspects of beamforming. Beamforming is performed in both transmit and receive phases of image reconstruction. So, with this, I would like to conclude the lecture.

Thank you.