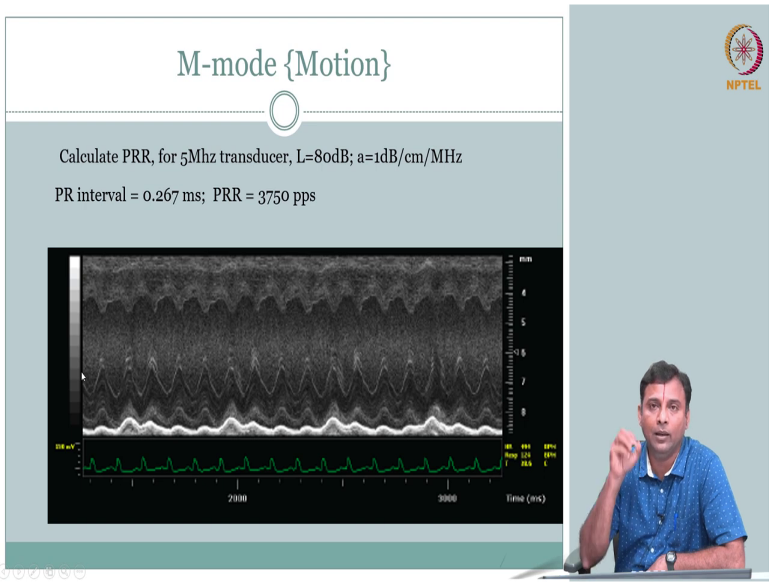
Introduction to Biomedical Imaging Systems
Dr. Arun K. Thittai
Department of Applied Mechanics
Indian Institute of Technology, Madras

Lecture - 38
Parameters of interest

(Refer Slide Time: 00:15)



So, now, we will talk about the extension I was talking about. So, this is that one location, I know how to calculate pulse repetition rate, I know what is the depth of imaging that I want, but that is at one location. A direct extension of that is what is called as M-mode or motion mode.

What is motion mode? Now do not get confused. This motion is not moving the transducer. The beauty about this mode is I told you that you get only at one location you are sitting, you are getting in the z direction in the depth direction the echoes, right. That is what your a line.

So, what happens, if that echo that interface, if that interface is moving. So, I sit in the same location, but there is a motion of the interface, right. So, where do you think this situation is available in your body. Well, if I sit in one location of course, we talked about doppler blood velocity, but there it was mostly scattering motion that we talked about. Not really the interface as we covered, right now, right.

Where else? Your heart, right. If I want to heart you have flaps that are opening and closing, the heart tissue itself, right. If I am hitting at sending my pulse, I am sitting in the same location and this heart is pumping, right; that mean the interface is close further away close further way.

So, I am sitting in one and listening to the echo, it will seem like the wall is going to come towards you, move away from you, right. So, the, so if I do time trace, right calculate the pulse. So, you can calculate the pulse repetition rate. So, of a 5 megahertz, right, loss is given. So, I pretend I want to do this heart imaging. So, I want to I am given a transducer.

How fast can I do? Just to get an appreciation for the number, if you have 5 megahertz a is 1 dB per centimeter per megahertz, that means, I am going to have my alpha to be 5 times 5 dB per centimetre 5 dB per centimetre, right. 1 dB per centimetre per megahertz into 5 megahertz will give me 5 dB per centimetre. Loss appreciable here is 80 dB. So, I can get L as 80 dB divided by 5, right 80 by 5, ok.

So, I can easily calculate my depth of penetration. Once you get the depth of penetration you can calculate the 2D by 2 depth of penetration by c, right. If you apply you can get your pulse interval or pulse repetition is going to be 3.75 k or 3750 pulse per second, right. This is what I can do.

So, that means, I send my first pulse, receive the echo signal, send the next pulse at after 0.267 millisecond, receive the echo, and I plot the time trace for it, right, my envelope signal, my a-mode signal. How will it look if I do it such that along the path there is a heart or something that is moving? Right.

So, you will get an image, you will get an image, this is one a line, right. So, what is the difference? The amplitude mode I showed you the envelope, right here because we make it as an image, you encode the bright the peak to be white and the valley to be black and everything in between to be your black and white.

Similar to the example problems that we did in you know when we talked about the introduction imaging, plotting a signal, 2D signal, and image of a 2D signal, visualizing it as a image. You quantize the third dimension as a colour. So, here that is what is happening. So, your amplitude mode, but this is one amplitude line. So, this is 0, this is your skin and this is going into the tissue into the body, right.

So, this one line is supposed to be one at one response to one pulse. I am sending the next pulse and placing it next to each other. So, this is a time axis. This is your depth axis. So, when I plot a line as a function of time, I get a motion mode. Why is this a motion mode? Notice that this interface is coming close going up. So, this is opening closing here see. So, skin you do not have much oscillations.

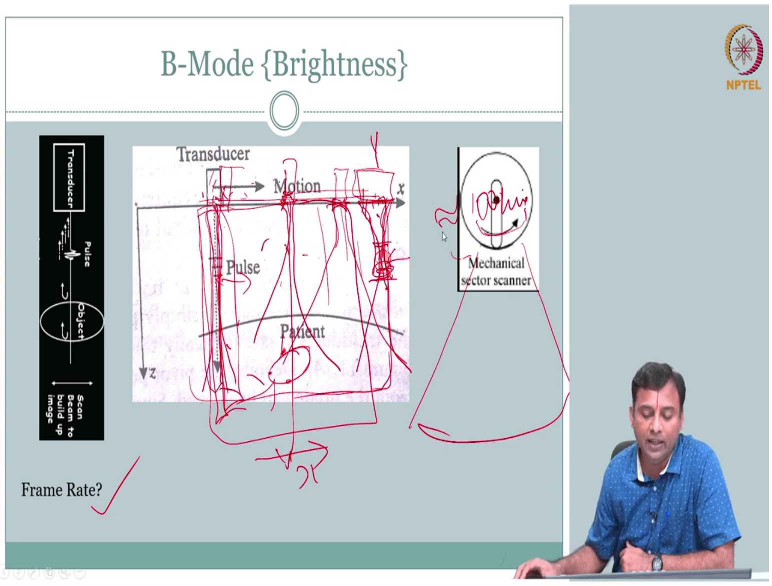
So, skin is not moving up and down that much. So, therefore, it is not oscillating. Whereas, along its path there are several interfaces very weak these are very weak scattering, right, whereas, this prominent interface that is moving, right within that path is you can notice. So, you see how powerful this is. This can visualize if the flap is opening moving, right the frequency with which; so, this is your ECG, right.

So, you can essentially look at this, and say look you can actually get very powerful information, even though it is just amplitude at one location you are keeping. You are just plotting it as a function of time, your a line as a function of time, different pulse, right. You are you are just stacking next to each other. This itself tells you the whole range of motion of the tissue that is opening and closing. You can get that information.

You can get the frequency of opening and closing. All these are vital parameters, right. So, you can get all that. So, you can visualize that information from this image. So, this is a motion mode. Mostly you see this in the scanner as one of the options, and it will be typically used when you are doing a echocardiography.

That is a whole field cardiography is you relating to your heart. Echocardiography will be a different you know department in a hospital, specialized scanner will be there. It is an ultrasound scanner, but echocardiography means its same echo principle works as echo principle for the heart, ok. So, in that you typically encounter M-mode.

(Refer Slide Time: 07:09)



Most powerful use will be what we call as brightness mode, right or B-mode. This is the sonogram, this is the typical image the you know the baby sucking the finger, right. The typical image that you see for ultrasound that is a brightness mode. Like I said already in M-mode, I just pointed out. What is that brightness mode?

In principle you have this amplitude mode, you have this envelope, right, if I stack that at, I do that at different locations and quantize the amplitude into different brightness, white being the highest you know the peak value, black being the floor value, anything in between is your grey value. So, it is encoded to brightness. So, that is why it is called as brightness mode.

So, you start out with the same amplitude mode signal, right which is which is very straightforward from our imaging equation. Only thing now what we need to do is, so you got one a mode signal. Now if I want to do image, what should I do? I should move the transducer, right I move the transducer to the next two location.

So, for example, if this is this we talked about z direction, depth direction, so let us call this as your lateral or your x direction. So, I have to now step to some x 1 comma y naught coma z naught and do the same wait after your depth of penetration, you trace all that, you send the next pulse, go to the next location. So, I go left to right, I built my scan one line at a time, right. I build my scan, one line at a time.

So, transducer I move the transducer, so this is the pulse, right. So, for simplicity this is what we put. But notice the challenge. So, if you want to do the scanning this is how they use to do at the beginning, right. You have a transducer, how do I move this? Correctly, so that it is registered, so I can get an image, right. So, the you your image as you see can be like this, right. Some organ is here, right baby is here for example, right. Your you this is the image that you are building.

So, you notice I can do this in principle from what we have covered so far we do this. In fact, this is how they did it, on fact, to do this more carefully they had a articulated arm, so that this goes in line. So, like how you have your a you know engineering drawing, right when you are exposed to an engineering first year course engineering drawing, you have this drafts, right.

So, likewise, you have a transducer that will be attached to a arm and the doctor has to basically move it, but it will it is a kind of engineered such that it will move in straight line, right at certain velocity. So, this is how they used to do it, ok. So, that is why it is registered, you can move. But you notice the challenge. So, this is straightforward. We are not going to spend more time on this. This is how it started.

So, you can imagine the same A-mode what we saw in the previous slide is M-mode, similar thing if I do the same amplitude, quantize it, put brightness, this will be at one location, next to location I move I do this. So, this will be your x direction, this will be your z direction, I get an image, where all the scattering will be different, right because of interfaces like this.

So, they will be scattered, but then the interface reflection coefficient will be probably more close here, more farther away here, farthest away here, right. So, that is how you see the outline of the baby. So, wherever there is a interface change or some other organ, right. This is how imaging is done.

The challenge here which we will try to address and overcome is if you do this you notice how do I step one parameter we talked about how soon I send the next pulse, right pulse repetition rate. But now the point is how much can I step. Say if I am going from left to right. Ideally, I need to be as close as possible. So, idea is I am building this image line by line.

So, first I get one time trace here, next this transducer is moved like this, right. I get the next. Even though the transducer is moved, right, so let me not clutter it here. So, you do the same process, say I am here. So, I can have different lines stacked next to each other, so I can form an image.

But this is a very simplistic, right. You see the challenge. When you have a transducer like this what is going to happen beam pattern, it is going to diverge, right. It will start and then it will we talked about this diversion, right. Not only that then you will say, we talked about having a lens. So, we talked about having a lens. Lens will do, ok, depending on you are still talking about like this.

Then, you might say, if this is the case then maybe I can have a bigger transducer element. This will probably allow me to have more narrow, all right. But then if I have this much, if I step in the lateral direction how I have to still step as fine as possible, but anything finer than this is not going to be, right, this is the narrowest, right. So, the narrower I step; that means, I will have to do lot more lines to cover the same distance, right.

So, that means, each location I am sending one pulse. If I have to construct a frame, an image frame which has how many lines. Say for example, typically we get say approximately 100 lines if you want to cover, right. I have to send 100 pulses, ok. But each pulse how much I am going to cover? Each pulse I am going to have certain width that it is covering. So, if I want to have a good resolution in the lateral direction, I have to have as narrow a beam as possible and I have to step as fine as possible, right.

So, all that is going to take more number of pulses. And your, if you are to do your beam width shaping you can only do the shaping so long, right. If you get this narrow it is going to be wider, only at this location probably you will have reasonable narrow width anything beyond that it is going to diverge again, right. This is the complexity. So, this is how you get it.

So, one of the other important parameters just to put all and the of course, that means, you have to start your motion, stop your motion, get the data till depth of penetration at that location. I have to go deep and come back. So, that means, I have to maybe halt here, maybe I can move slow, but the point is there is a time to have this motion taking place. Start stop or go slowly, so that you can receive from the deepest location, whichever way you look at it, if one another constraint is your apart from your resolutions that are dictated by the frame beam pattern, right to execute this, execute this scanning also takes time.

So, one of the important parameter is when you talk about one dimension, we talked about pulse repetition rate. Now, if you are talking about image, you always encounter this frames per second, right, frame rate. That is what you will encounter. What is the frame rate? How much time it does it take to get one frame, image frame?

Here in one image frame, you get by sending multiple pulses, 1 pulse at 1 location. So, the number of lines I have, that many number of pulse I need to send, ok. So, what is your frame rate? What is your frame rate? Number of times your pulse repetition rate, and how many pulse do you need to send to obtain 1 frame. That is your frame rate, ok.

Of course, this is linear motion. You could also do, right sector, right you connect this and you can articulate it at an angle. So, that way if you do it this way your image will be like in this format, right. This will be rectangular image. This will be a pi kind of image sector image they call, ok.

So, this is how it was done. I mean the reason I just want to leave it at here is this has lot of challenges as you can see. I can have only one focal location because the lens is going to be manufactured with one particular curvature. So, I am going to have only one focal depth that I can have. So, all my; and then I cannot if I have a big one I can have narrow, right. But then I am still averaging over all the area to get one thing, right.

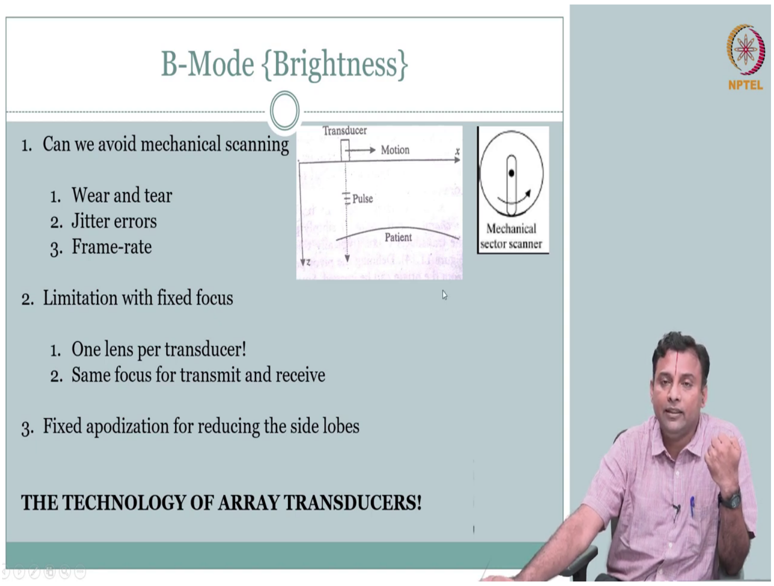
And the more wide and more narrow I have, more shorter will be my depth of focus, right. So, my resolution will be spoiled. But if I have, the other hand if I have a smaller transducer then the divergence will be a issue and I cannot have focusing effect, right. So, and of course, that is the case my step size also should decrease and therefore, your time for acquiring the data is going to increase.

So, all these trade offs makes it that it was the way it was done until 90s for example, right. So, you had your frame rate also coming into picture. You wanted to see real time, you want to see the baby sucking, right, you, so that means, you have to do it faster than, you have do better quality that.

So, the whole bench marking of ultrasound images changed, right by instead of scanning it mechanically, the whole idea of electronic scanning using array transducer, having multiple elements. Instead of having only one transducer like this and moving concept of array transducer kicked in in the 90s. And that kind of changed the whole landscape of ultrasound imaging.

So, what we will do here is just take a pause and then continue with array transducer and wrap up the image formation, and image quality we are interlacing already, right. I am so, in that sense, image quality and image formation, in relation to how we are acquiring the data, right, how we are scanning, we have coupled it, ok. So, we will stop here. We will wrap up the ultrasound introduction to ultrasound imaging in the next 45 minutes.

(Refer Slide Time: 19:40)



So, let us continue with the B-mode operation of an ultrasound. This is predominantly the most dominant imaging mode. When they say ultrasound image this is the mode that typically comes to mind. So, amplitude mode has its role, but when we talk about images, we typically associate an ultrasound image with what is a B-mode image which is brightness mode.

So, what we did see is carrying along with the same logic of having a A-mode, but then translating the A-mode, right, scanning the A-mode we could create a image, however, right.

So, this is what we saw. So, you could use this transducer. You could get one A-mode, right, the a line we call, amplitude mode, you operate amplitude mode. And the next pulse you move this and this way you could scan and get a whole x by z image, right. z being the depth x in this direction is the lateral direction we refer to. So, this will be the image.

However, this has lot of, I mean this is how it was practiced, right. Of course, with instead of just moving it with hand, they used to have a articulated arm, so that you go in a line. But then there are a lot of disadvantages, right. So, this is not currently in vogue.

However, the logic is very powerful because we covered physics and then we translated this to this use of it. So, what are the things that we were able to do here, which is a which we see the reason for doing it, but it is kind of a disadvantage or its kind of a limitation that would allow us to seek for better advancements in instrumentation, ok.

So, first is can we avoid the mechanical scanning? Yes, the idea is the I the transducer is helpful. It in sense the wave, receives the wave, we can get the A-mode, we gone through the physics, right. It made sense. But then, to engineer it to an application, the instrumentation there was a limitation. So, can we avoid, instead of doing this mechanical scanning? Very similar if you look at it from you know first generation CT you know to the advanced CT, that we covered similarly. So, you had one transducer and the transducer had to be moved. Can we avoid this?

In fact, there is lot of disadvantages, right because you have wear and tear of the mechanical parts, motors, and then you could have jitter error because you are moving, stopping, taking the data. So, you know unless you completely come to a halt, you will still have start and stop. So, there will be some errors. If you want to do that, how many times how many time should you do that, right. So, it will take forever. So, the frame rate will be extremely slow, ok.

Unlike CT or in electromagnetics, right the wave here speed there speed was not an issue, whereas, here speed is the sound has to travel. So, that is a very fraction, right of compared to your light or electromagnetic wave. So, frame rate will be severely limited, if you have to start stop at every location, wait for the deepest location to the depth of penetration that we covered, right. So, all that is a challenge.

So, ideally, we want to avoid this mechanical scanning that way where we could do better, right on all these problems. We should we should be able to eliminate all these problems to the best possible extent, ok. So, that is to do with just mechanical design aspect or articulation.

Is there anything to do with the image quality that we are limited by operating it this way. Well, we talked about focusing that what was the problem, focusing was good we could get our lateral width as small as possible light at the focus, but then the challenge was you can have only one lens because this is a physical acoustic lens if you put it in front of the transducer, so each transducer will have one focus.

So, if you want to have a focus in different depth for example, you need to take another transducer or just live with this, move the, move the patient, right the that object can be moved up and down, so that it fits the focus. So, in some sense it is very limited you have only fixed focus. Not just fixed focus on transmit the waves that are sent out, even they receive, right the echoes that are coming back, they are also going to have know, you are going to have the fixed focus effect which was done for that particular curvature of the lens.

So, this is a big challenge. You want ideally all the images, ideally, all the pixels in this image to be at the focus, right. But here you are clearly limited you have only one transducer which comes with the fixed lens and therefore, there is only one focus. So, that is a challenge, right both transmit and receive use the same lens. So, you have a problem.

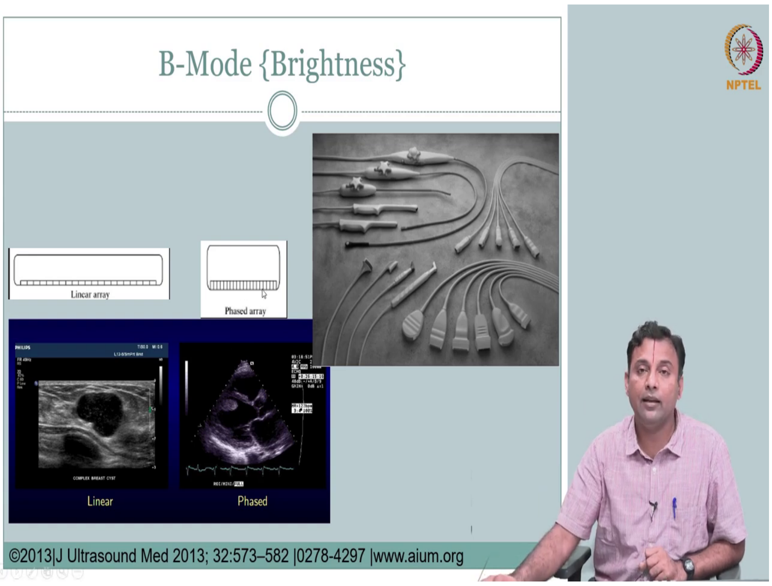
What else? Is there anything else that comes to your mind? From a image quality perspective focus is a big issue, right. Well, of course, other aspect was your side lobe reduction, right. We talked about having apodization. So, you could in front of the transducer, why give weight, same weight to the centre and the edges. You want to give more weightage to centre and as you go away from the centre of the transducer towards the edge of the phase, you want to have a smooth, right, Gaussian, right. We talked about that. So, you could have a material that does the apodization.

But clearly you know from your signal processing, similar concept you would have been familiar filter design, right. Main lobe to side lobe or ripple effect, you have a rectangle window or as a Gaussian window, right. Same logic, I said this in the spatial aspect here. So, that means, you know there are so many different windows that are possible, hamming, hanning, whereas if you end up doing one material which gives preference weight to the centre as supposed to the; you can have only one profile, you can have only one window function, right. So, that again fixed apodization.

So, that is a challenge. I mean we would like to increase the image quality, to do the best possible. So, these are all major limitation and so all of this got kind of this background pressure of doing better quality image in real time, overcoming this limitation kind of got addressed and lot of migration, transition, lot of development in ultrasound, as we see today took place because of advent of the array transducers.

What do we mean by array transducers? Instead of one element that you have here you have multiple elements, right.

(Refer Slide Time: 27:02)



So, that is your you can see a, I found this imagine one of the journals where they talked about a it is a clinical journal where they talk about how to choose a transducer for a particular clinical application. As you can see depending on the application you your size and shape of your transducer changes.

So, you would see some of them for example, here, you will still use the single element that we covered so far, mechanical scanning. Why? Because say for example, transesophageal, right, you have to send the transducer through the opening. So, in trans intravascular, right, you want to send it through the vascular, blood vessel, so that you can go inside and see.

So, all those things you cannot have you have to have a size of the transducer that is small enough that it can go into the body. So, you could have, you have several different sizes and shape depending on the application; single element with mechanical articulation, right two different types of probes that you see here, ok.

Predominantly what we will cover in this course is the underlying concept of how array is used to form an image. So, we will not go into detailed specific application transducers. So, we will cover generic say for example, you have your linear array, right where elements are positioned next to each other along the line. So, these are different elements, different piezoelectric crystals, independent crystals, that are placed next to each other in this linear array form.

This is called as a phased array. Here also you notice that it is the array is, I mean the elements individual elements are placed next to each other. It is also in line. But it is called phased array just to differentiate from linear array operation because we will talk, we will cover this phased array subsequently. Because here you notice the size of the element will be different, and the distance between the elements is designed for a certain phase, ok.

So, we will talk about that. That is why its phased array. Even though it looks linear this is phased array because the elements are placed, so that you know at a particular separation between them, the elements are separated by a particular distance in order to capitalize on the phase to get some construction conditions on the phase of the waves that are coming from each element. So, we will talk about that. So, these are very popular.

Of course, there is also a curvilinear, right for abdomen. When you have larger area to cover, right you want even bigger head, wherever you can place the probe on body where there is no constraint on axis, ok. So, depending on the application you have different probes. So, what we will cover is we will our idea is fundamentals just to in get an idea on the subject.

So, we have covered A-mode. Instead of mechanically translating it, mechanically you know steering it how do we do the same thing, how do we accomplish the same thing using this transducer array that is what we will cover. So, next 45 minutes or so, is where we will complete the module on ultrasound is probably going to be the single most important piece of topic that you need to know in ultrasound as far as ultrasound imaging is concerned because this is where the jobs are.

What we covered in the physics, what we covered with mechanical you know the beam focus, all the concepts of physics, and the single element transducer is necessary. But then, most of the application as you would see here, but for some specialist application most of them have moved to array and digital, right.

So, how do we; and the physics that we have understood so far the wave equation and what we said, how do we execute it, how do you engineer it using this transducer, how do you dictate this transducer to do the same physics that we covered so far, right. Of focusing you know scanning in different directions, how do you do that, that we will cover at least give a tip of the ice berg kind of overview, ok, in the in this next 45 minutes.

So, I think it is very powerful. Please pay attention. Then, you look at several different animations, text books. I hope you cannot use this 40 minutes of an excuse and. say, I will listen to this module. So, I have you know I should I expect it to be crystal clear in my mind.

That is not going to happen. This along with you going reading the text, different text, see animations in the you know website. You just go these are very very you know powerful material, several good animations are there. But once you have a formal orientation you will be able to look at it with the critical eye and understand further, ok.

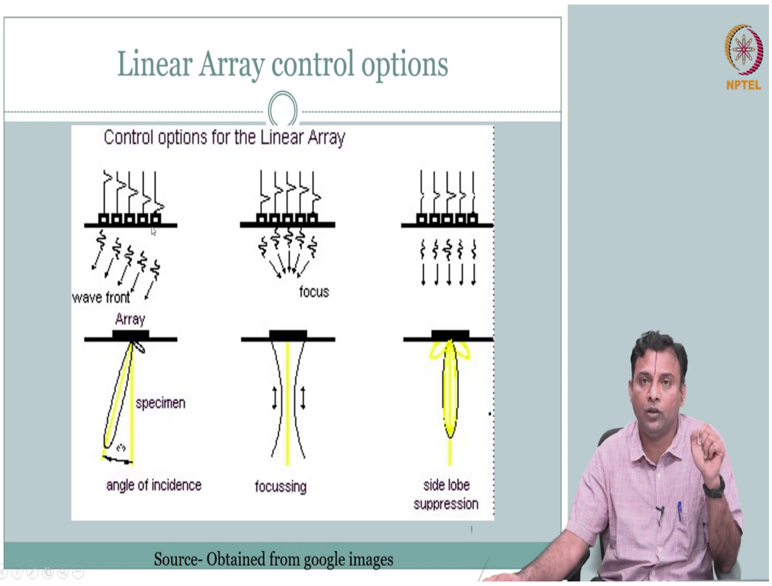
So, let us jump in first to see how we use this phase array. So, before we jump we will have a overview. So, the why do people use different transducers for different applications? So, your image format will also be different. So, linear array you will get a typical rectangle, right. So, like this. Whereas, in phased array you notice it is a pi shaped or sector shaped you get.

How do we get this? From your a line, right. So, A-mode we will cover now. So, in fact, this we will not cover detail. This is something that we will cover in detail and then this becomes one particular condition of the operation of this, ok.

So, we will start with phased array. How do we; see from what you know so far, right do not worry about this lines, elements. If you had a single crystal of this width, right, what would you have? What have we covered? You excite. It will go. You get one a line.

What you see here is you have one a line, you have another a line, you have another a line, each one has been fired at a different angle. So, instead of this mechanical articulation like a sector that we talked about, here the same array is standing there. It is able to send two different directions and collect a line. So, let us see how it is done, ok.

(Refer Slide Time: 34:36)



So, why we are able to do? So, different functionalities, why we are able to do? The reason is here. Essentially, what happens is it becomes complex because now instead of having only one lead, right. We have a transducer, we had one wire coming out. So, you supply electrical voltage, electrical pulse, it vibrate, sound goes out. When the sound comes on hits, it vibrates, you get your electrical out.

So, there was only one lead wire, if you look at the previous piezoelectric crystal single element that we cover, piezoelectric transducer. Whereas, here what you have is multiple crystals. Each one has its own control, each one is acts as a independent channel. So, you have electrodes for each of the crystal.

So, now, you see the challenge. If you have a smaller crystal you have to have all the you know electrodes that are also correspondingly a small, not only that there should not be cross talks, right. So, you have many of these, then you have complexity goes up. But the point is the advantage is you have all these crystals next to each other, each one can be excited.

You can independently send electrical voltage here, and whatever hits this crystal alone, you would be able to receive the corresponding voltage and play with it, right, corresponding signal you can get. So, now, you notice the advantage. Now, I can independently operate all of this. So, I can send; remember how your wave physics that we covered. So, when you hit an element, right. You excite, what is happening? If it is a point source, you are going to get a spherical wave, right.

So, what do you see here? Now, my elements are getting smaller and smaller, and many of them are placed next to each other. Instead of having one full transducer surface where we integrated, right, integrated over the full surface area s of x comma y, right s of x naught comma y naught, right. So, here you have many of them. So, I could actually integrate only over the small area and it comes up.

So, in some sense, there is a localization. So, if only this is excited, this sends out a pulse wave, this sends another pulse, this sense another. So, I have control over how to excite them, right because I am the one who is supplying the voltage. So, I can supply after a delay. So, I could send them such that the plane wave front that we talked about, right, all of them start to go in a particular direction, right. So, this is what we call as (Refer Time: 37:26).

So, the advantage is you could do that not just that why do linear fashion. I could give such that, right, I could delay excite the elements with certain pattern such that you have focusing, ok. Concept is very simple. If I excite, we will cover this mathematically, but the idea here is it is all very simple. You create a wave.

So, if you excite this, this is going to give a mechanical pressure wave. This pressure wave is going to start to go out, right. The moment it leaves, it is going to go out in the medium. So, the idea now is if I if I want to focus at a particular location, medium let us assume as some velocity c, right.

So, I know the time in which this is released. So, time arrival of this to that particular location is going to be ideally we want this wave and this wave and this wave and this wave, all of them should come in phase coherently at a particular location which is your focus.

So, clearly you can see, I can manipulate. This one I should send first because it has to travel a lot of distance, right be to come here. At least lot more than; this is the shortest path. So, if I want everything to come to focus at a particular location, I can excite this hertz such that this will be excited last because it has to travel the least distance because all of them assume same speed in the material. So, this I have to send earlier, this I have to send earlier, probably symmetric.

Then what will happen? And then gradually, reduce the time, right; send after some delay you send this, and finally, you send this guy. What will happen? All of them will leave the transducer at different times, but then they all at will reach at a particular location at the same time which is basically they are all focused, they all coherently add up at a particular location. So, you can control all this.

So, advantage, now I do not need a physical lens. All I need to do is I should manipulate the time delay when I excite which crystal. If I play with that, I could get focus wherever I want, how much ever focus tight, how tight you want to focus, right everything can be manipulated by manipulating the sequence of excitation.

Last part we talked about apodization. What is apodization? Weighting the amplitude, right. So, that is no big deal. We already talked about; when you hit the voltage part maybe there only, I can give more weightage to the centre, as you go to the sides, I could reduce it. So, I could have apodization function, with based on that I could give the amplitudes at the transmit itself, right. So, here I have a higher amplitude, as you go to the sides, I have lower contribution.

So, in some sense, the transmit apodization, you can excite the way you want you can try hamming, hanning, you can do whatever you want. There is no fixed apodization material because I have control over all of the crystals separately, independently, I can give whatever same wave from at a different voltage and the profile of this can be your window function, clear. So, it is all electronically done, ok. And that is that.

So, all the major limitation that we talked about with respect to mechanical scanning with the array, the advantage of having control of each of the crystal separately gives of the flexibility to overcome scanning whichever direction I want I can scan, however I want to focus I can focus, whichever apodization I want to apply I can apply. Pretty neat, right.

So, let us see, let us jump in. Let us see how to, how to execute this in principle you see this, but how do you calculate this, how do you know what is the exact analytical formulation, right to execute this. After this, you can try out different things. But the general idea of beam steering, beam focusing is something that we will cover in the next few slides, ok.