Introduction to Biomedical Imaging Systems
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Lecture - 34
US Doppler and Instrumentation

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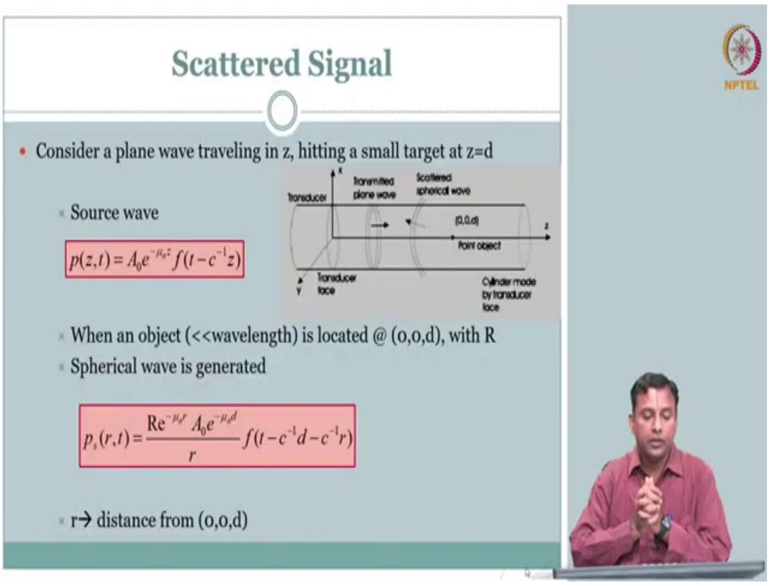

Scattered Signal

- Consider a plane wave traveling in z, hitting a small target at z=d
  - Source wave

$$p(z,t) = A_0 e^{-\mu_a z} f(t - c^{-1} z)$$

  - When an object (<<wavelength) is located @ (o,o,d), with R
  - Spherical wave is generated

$$p_s(r,t) = \frac{\mathrm{Re}^{-\mu_a r} A_0 e^{-\mu_a d}}{r} f(t - c^{-1} d - c^{-1} r)$$

  - r→ distance from (o,o,d)

Ok, So after understanding the ultrasound wave equation right, we reduced 3 dimension to essentially a 1D propagation and in that we talked about interaction of this wave with the material medium right. Namely, the important interactions that we captured where, reflection coefficient, transmission coefficient, angle of incidence, angle reflection right.

So, the that was one thing and then that was a specular reflection. And then what we called as diffuse a reflection of scattering and we ended up having a signal model for the scattered signal. So, in our case it is the pressure wave that is reflected from a point which has a reflection coefficient. So, this is the part where we identified somewhere what is the physical meaning of the signals that you are going to record and see in ultrasound image, it is going to be related to this reflectivity. How is this 3D distribution of reflectivity to ultra sound right, that is what we are going to capture.

So, before we proceed further on the instrumentation and image equation there is one another interaction that is important that we understand. So, so far what we have done is we have defined the wave propagation and then how does this wave interact? More specifically, when it encounters an interface right where there is two mediums two different mediums on either side right, when a wave encounters that what happens to it that is what we have seen so far.

Now, we will stretch a little bit beyond and ask our self ok, what happens? Right, if this interface or this acoustic scatterer that we model if that is not stationary. So, the wave is coming. So, the wave is moving its travelling, but then it is encountering an interface or a a point object which is not stationary which is moving right, then what happens? Ok. So, that is important as you can see in biomedical context right, there where could the motions come from?

Well you could have the whole specular surface of your lungs for example, right can go up and move in and move out, so to some extent that is possible, but more importantly, what is moving fast? Our blood, right. So, it will be interesting to understand what happens when you have a wave that is going to hit some interfaces it can be smooth interface or it can be you know scattering that can come back because of the size is much smaller than the lambda, what happens to it? Right.

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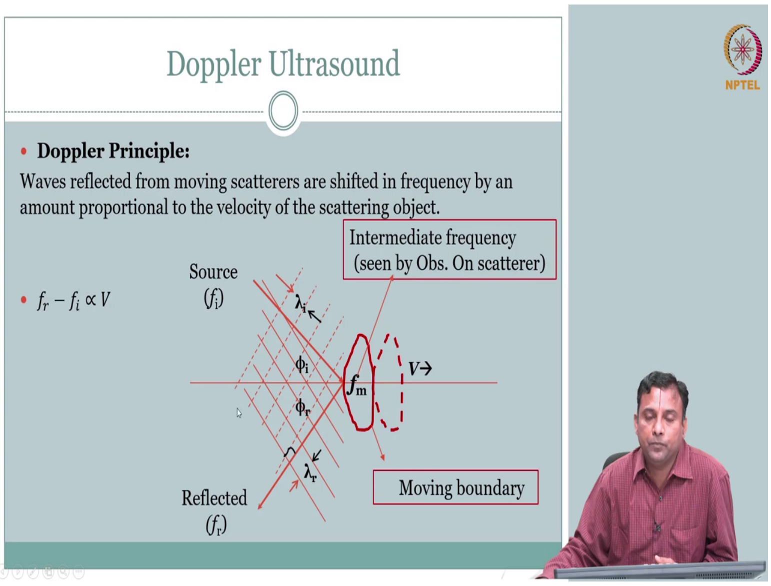

Doppler Ultrasound

- **Doppler Principle:**

Waves reflected from moving scatterers are shifted in frequency by an amount proportional to the velocity of the scattering object.

- $f_r - f_i \propto V$

So, in this context is where the concept of Doppler ultra sound is exploited. So, what does Doppler principles say this you might be knowing from your high school right you would have been told what happens when a train or an ambulance which is siren right when it is approaching you, what do you hear? Right and when it is going past you what you hear, what you perceive? Right.

Beyond just the loudness that is getting increased as it approaches right there is this frequency there is a shrillness that will also have. So, if the vehicle the sound source right the siren is on top of a vehicle. So, the vehicle is moving you are on stationary observer. So, there is a relative motion between the observer and the source ok. In such a case you would have been introduced this concept of Doppler principle which says oh when you do that your the frequency shift right. So, there where is a pitch that is different what you hear the shrillness is different.

So, the change in frequency is proportional to the velocity the relative velocity this is what you would have you know vaguely remember from your high school. Typical examples of a train which is blowing horn or a siren in an ambulance where there is a relative motion between the source and the observer is something that you would have been familiar with.

So, the same principle when applied to ultrasound signal not sound signal that right the examples that we gave. When it is done to ultrasound signal which is not a big deal only the frequency range is different right. Then that is what is called that is that aspect is called Doppler ultrasound which is exploited mostly for you know moving objects, what does moving objects? Mostly it is blood ok.

So, waves reflected from moving scatterers are shifted in frequency and the more important thing is that frequency is proportional the amount is proportional to the velocity of the scattering object. So, in simple idea if I can engineer I can send the sound wave with certain frequency right. I send an ultrasound wave with a certain frequency, if I can receive an ultrasound wave that is getting reflected from an object right and that object is moving with the velocity.

So, I can have my I can have some ways and means to know what is my receive frequency, I can know what is my transmitted frequency. So, the difference between them is proportional to the velocity right. So, if I can measure this then somehow I can get an idea of an object that is moving with a velocity V ok. This is cool right, I can sit outside send a frequency in, receive a frequency, analyze the frequency and tell that something is moving with certain velocity. In our case it is going to be blood mostly right. So, it is very cool neat principle that is exploited here.

So, what we will do is we will take a very rudimentary approach just at a at a very you know two step process right, we will just try to understand where what this proportionality constant is right is proportional. So, we will have to set up per problem and quickly recognize what proportionality constant is ok. So, let us take a situation this is very similar to what we started before right when wave interaction with the medium.

So, you have a plane wave that is travelling right a plane wave is travelling, only thing is instead of an interface that was stationary I replaced that with some object which is moving. So, in other words you have a boundary that is moving ok. So, that is the only difference otherwise you see that these are the plane wave fronts, when it is coming the other one is the plane wave front that is coming back. So, you are going to have reflection right and.

So, you have a angle of incidence you have a angle of reception right, incident angle of reflection and then you have your wave length of the incoming right, the source. And there is a wave length with which these waves are going after getting reflected what is new here is this f m, what is this f m? Oh, this f m is again another frequency which you call as the intermediate frequency essentially now the object is not stationary the interface is not stationary.

So, if I sit on the interface right on this object what is the frequency that I will see of the wave fronts that are coming ok. So, this is my frequency as observed from the object and it has a velocity V in this case I have put the velocity to be going in this direction to the right ok. So, given this proposition, what do we know already? What do we want to do? Well, we know the big thing the big thing theme is somewhere we will have to find out, what is this f r minus f i?

So, the easiest way is start writing it out right from the fundamentals. So, the idea would be we need to relate you are sending a frequency, you are receiving a frequency these both are related to this f m right this object that is there the frequency that is observed when you sit on this and there is a motion of this object.

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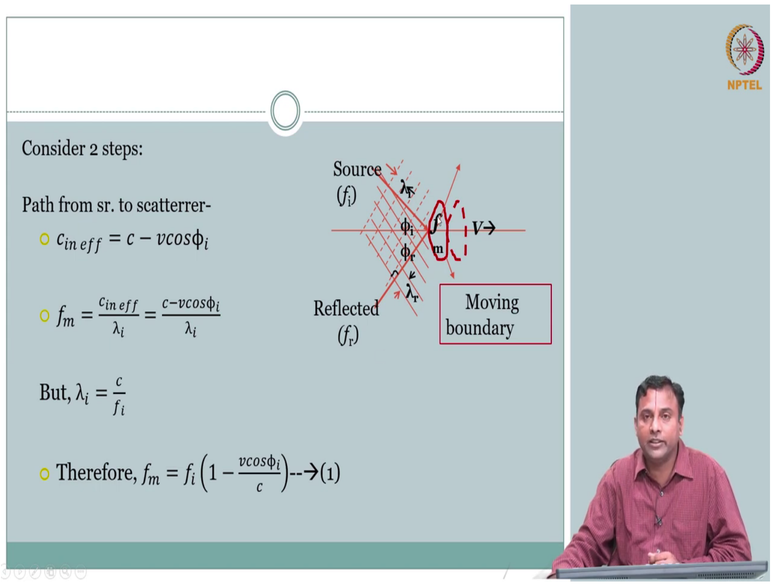

Consider 2 steps:

Path from sr. to scatterrer-

- $c_{in\,eff} = c - v\cos\phi_i$
- $f_m = \frac{c_{in\,eff}}{\lambda_i} = \frac{c - v\cos\phi_i}{\lambda_i}$

But, $\lambda_i = \frac{c}{f_i}$

- Therefore, $f_m = f_i\left(1 - \frac{v\cos\phi_i}{c}\right) \dashrightarrow (1)$

So, what we will do is we will start with two step process, first we will see what happens from the source to the scatter. So, in that sense if I sit on the object here, what is the velocity with which what is this oh these are plane wave fronts right, different phase right I am high rarefaction or compression right high pressure low pressure is oscillating. So, what this line indicates is iso plane right what some pressure. So, typically you can consider that as a peak pressure right peak positive or negative. So, this is the distance between them is one cycle is your lambda.

So, in some sense what is the velocity with which this phase is hitting this interface oh ideally it would be just the c right the phase velocity in the medium, but now this object is also moving with a V. So, there is going to be a effective velocity right because of the relative movement right there is going to be a effective velocity of the incoming waves ok. So, that will be c in effective is c which is your without any relative motion minus the component of v cos phi correct yeah.

You are moving in this paradigm you are moving this direction the waves are arriving right. So, you are moving away while the waves are reached. So, in some sense it is slowing down at least you will feel that it is coming slower right. So, that is your c effective in ok. So, this is my c in effective what do I what do I know ok c in is one idea, but then what is the relationship between c lambda and then f this is what we are going to exploit.

So, what would be your frequency in the medium right you intermediate frequency the frequency with which this is observing these phase fronts are hitting right. So, frequency will be c by lambda, in this case it is c in effective by lambda i incoming waves. So, lambda is in the medium this side of the incoming wave c in effective is the velocity the effective velocity as seen by the observer. So, the frequency the intermediate frequency observed by the moving observer is going to be c in by lambda f is equal to right sorry c is equal to f lambda, if you remember that ok.

So, c in effective is your c minus v cos phi ok. So, you have your frequency intermediate this much is fine of course, there is one more item here lambda i, what is lambda i? Oh lambda i I know from it is in the medium nothing to do with this guy this is what I am sending and it is in the medium. So, lambda i is related to your c and f i right.

So, lambda i is c by f i that is in the medium you are transmitting in the medium straightforward lambda is equal to c by f ok. So, I will just substitute this back. So, that I get my f m in terms of f i right of course, with this factor f m is equal to f i times one minus v cos phi i by c ok. So, this is one equation this is based on source coming to the observer right of the object that is moving.

So, now what is the other path? Oh the other path is after it comes hits here there is a wave that is reflected and going back right this direction. So, now, we could do similar argument and understand what would be the effective velocity of the waves that are going out ok, what could be the your f m cannot change right you are catching you are sending out right reflecting. So, your f m cannot change, but your c out effective can change. Of course, there is a lambda that we need to check ok.

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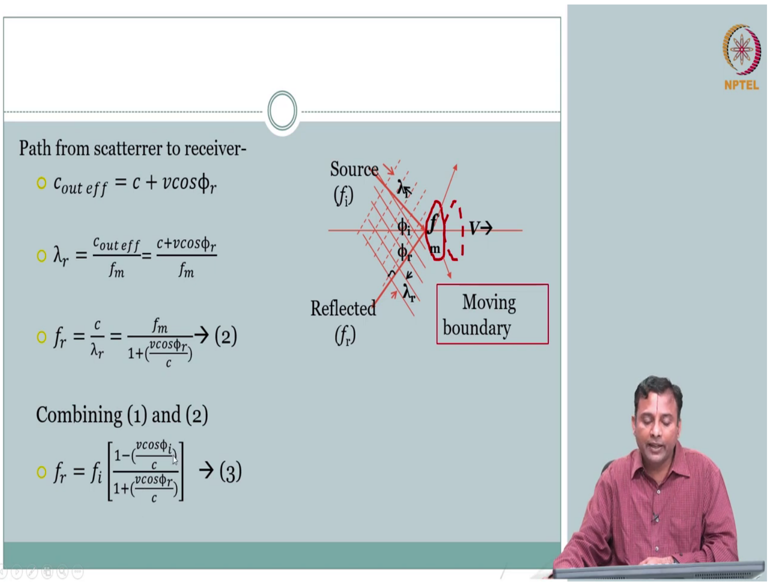

Path from scatterer to receiver-

- $c_{out\,eff} = c + v\cos\phi_r$
- $\lambda_r = \frac{c_{out\,eff}}{f_m} = \frac{c+v\cos\phi_r}{f_m}$
- $f_r = \frac{c}{\lambda_r} = \frac{f_m}{1+(\frac{v\cos\phi_r}{c})} \rightarrow (2)$

Combining (1) and (2)

- $f_r = f_i\left[\frac{1-(\frac{v\cos\phi_i}{c})}{1+(\frac{v\cos\phi_r}{c})}\right] \rightarrow (3)$

So, we will now take the other path, where you are starting with the scatterer and going towards the receiver. What is the effective velocity the wave that is going out of this observer right in the incoming path we were sitting and observing the phase velocity, the phase that is coming and hitting you, what is the velocity while you are moving? So, now while you are moving it is reflected and sending out back ok.

So, your c out effective is c plus v cos phi r. So, c out you have ok good then oh we could also write our frequency m right. So, what we will do is we will recognize c out, we know what is lambda r lambda r is the wave that you are sending or the velocity with which you are sending out. Because the reflected wave is going at certain velocity which is relative velocity because this is moving otherwise it is the same medium.

But now the difference is it is a reflected wave is having an effective velocity based on the interface that is also moving that is why this is c out effective by f m ok. So, this is the lambda r. So, if I substitute for my c out effective I can get c plus v cos phi r by f m. So, what can we do? Oh I have a f m here I had a f m when I did source to one path f m is supposed to be same right.

So, I can quickly move around I can quickly move round. So, your f r is equal to c by lambda r right f r is c by lambda r, but then I can substitute for my lambda r right, if I substitute for my lambda r and then here there is a c right there is a c here. So, you can make that 1 plus v cos phi r by c this becomes your second equation. So, you notice that from here you can have f m is equal to f r times 1 plus v cos phi r by c.

So, from equation 1 and equation 2, if you combine right because you have f m in both. So, you can eliminate f m and relate f i and f r. So, f r is equal to which is our objective right. In fact, this is not our objective, objective is we have to get to f i minus f r. But at least we are now in terms of f i and f r this intermediate frequency is gone.

So, f r is equal to f i times this guy. So, quickly what we need to do is this is good, but then you have 1 minus by 1 plus a fraction what is this fraction, oh you have some v cos. So, velocity component of this moving object moving interface with the c, c is your velocity of phase velocity is your velocity with which the speed is sound is moving.

So, you know for most cases you can you will realize that v is much smaller than your c, c is what? In tissue it is about 15, 40 meters per second. So, you know if you contextualize you know in human body blood even in aorta where you have know we are talking about 30, 40 centimeters per second. So, v is much smaller than c what that helps us do is you have this 1 minus a fraction by 1 plus a fraction.

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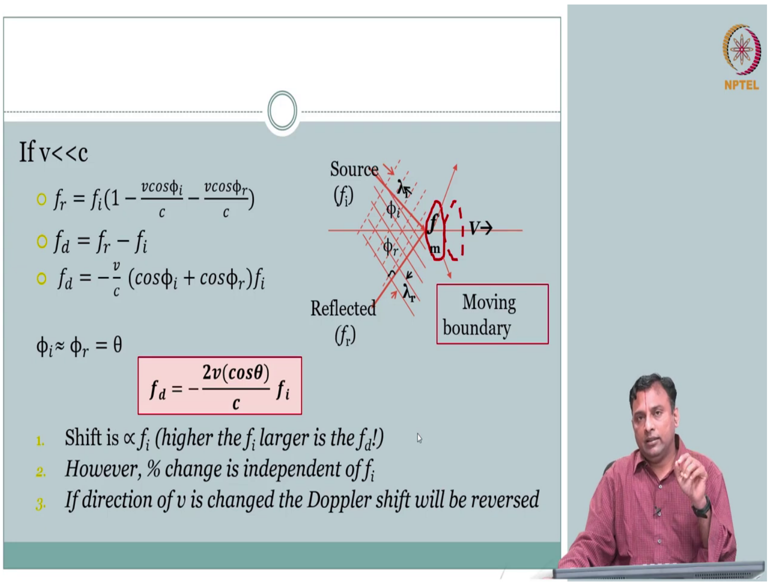

If v<<c

- $f_r = f_i(1 - \frac{v\cos\phi_i}{c} - \frac{v\cos\phi_r}{c})$
- $f_d = f_r - f_i$
- $f_d = -\frac{v}{c}(\cos\phi_i + \cos\phi_r)f_i$

$\phi_i \approx \phi_r = \theta$

$$\boxed{f_d = -\frac{2v(\cos\theta)}{c} f_i}$$

1. Shift is $\propto f_i$ *(higher the f_i larger is the f_d!)*
2. *However, % change is independent of f_i*
3. *If direction of v is changed the Doppler shift will be reversed*

We can try to make use of this fact that v is much smaller than c. And therefore, we can retain only the first order terms. So, we can write f r is equal to f i times one minus v cos phi i by c minus v cos pi r by c ok. So, quickly from here you can see that we are slowly getting to where we want, what we want? f r minus f i f r minus f i is your Doppler shifted frequency, Doppler shifted frequency is f r minus f i is going to be this v cos right v by c cos of phi i plus cos of phi r times f i ok, very interesting situation ok. So, now what we will do is we will pretend oh phi i equal to phi r ok if that is the case let them be equal to some theta for example, right phi i equal to approximately equal to phi r equal to theta.

If you do that you get this equation, what is this saying? This is saying the Doppler shifted proportional to v that is what we started out right. Oh here you see f r minus f i is your f d is proportional to u v of course, you have few other terms here. So, you have your cos theta because it depends on the angle relative orientations and your speed of sound c, more interestingly it is also dependent on f i ok. What that tells you is if I want to increase the shift shifted frequency Doppler frequency Doppler shifted frequency I can also increase my f i ok.

So, this itself is not a big deal. So, I can increase my Doppler shifted frequency if I increase my f i, so shift is proportional to f i. So, higher the f i larger is the f d, but notice however, that this part right this part is not dependent on the frequencies it depends on only on the velocity and the speed of sound. So, in some sense the percentage change is independent of your f i ok. So, the percentage change is independent of your f i. So, of course, you see a a negative sign here right. So, it depends on the frequency the direction of v is changed if the dop.

So, here what we started as velocities in this direction, what happens if the velocity is if the interface is moving towards the source right? So, this negative sign or positive sign depends on whether the object or the scatterer is moving towards the source or away from the source right. So, typically you will notice that it will be color coded right. So, when a when blood in a biomedical ultrasound when you have Doppler to visualize blood flow then if it is a red color blood flow very positive that means, the blood is flowing towards the transducer.

When you get a negative velocity that means, it is moving away from the transition that will be coded in blue ok, so that is just a sin convention ok. Its the from a simple physics point of view this is what is Doppler principle, but then when we actually exploit this for imaging there are bunch of tradeoffs that are involved because the whole idea is you want to estimate the velocity you want to preferably place the blood inside the vessel and you know register it against the b the structural image right of the organ.

So, where is that vessel? Inside the vessel something is flowing. So, typically you have to do the imaging ultrasound. So, now, what we will see subsequently that you have seen the gray image gray scale image right of the baby sucking right in the first slide we showed. So, typical ultra sound image on top of it you will show where the velocity is happening.

So, in some sense it is little more complicated from a instrumentation point of view because this is an add on to the structural image. So, we will leave the physics right now we will jump on to the instrumentation. So, with this we will complete the physics of ultrasound. In fact, slightly different from the text book approach where the subsequent topic of beam forming, beam pattern is discussed in the text.

I would like to treat it slightly differently leave it here leave the physics here jump to instrumentation and in the context of instrumentation we will talk about the signal right the beam pattern that is covered.

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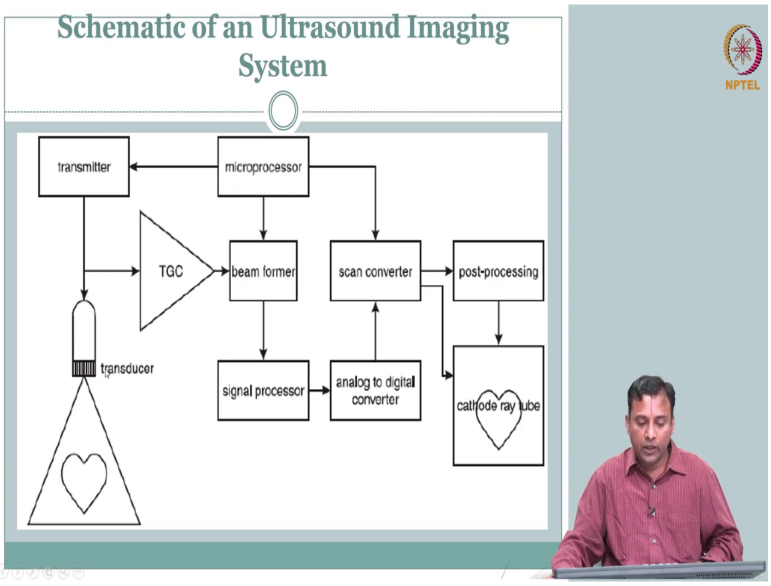

Schematic of an Ultrasound Imaging System

So, we will quickly move on to the instrumentation aspect of ultrasound. So, a schematic of ultrasound system is as shown here, what is important to notice is there are several different blocks ok in the spirit of keeping this to a introductory level right. In all of these pieces each of the block there are intricacies and then how you combine them is going to dictate the various tradeoffs that are involved for simplicity we will kind of take on only on the major components here.

So, we will, so there is this transducer. So, the idea is you have to generate ultrasound wave send it and then perhaps receive. So, the source and the detector right similar thing X ray tube and the detector. So, like that these are this is a major guy. So, transducer as we will see is an important aspect because it is generating the sound waves and also receiving the sound waves ultrasound ways. After that it is all about converting it into some sequencing again we will talk about beam former as well to some extent.

What we will not talk about is all this scan conversion, ADC, post processing, display all this we will go little light ok. This is an important aspect here this along with beam former this part is a very important aspect which connects your physics and what you are going to get in the image the quality of image and the image itself, the different types of image that you can get. So, we will try to give a very bird’s eye view on this big picture, but focus little bit more on the major components ok.

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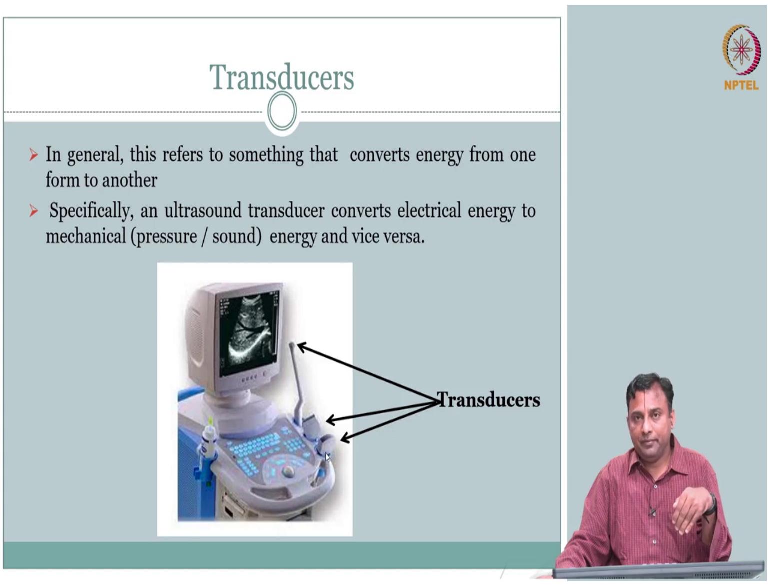

Transducers

- In general, this refers to something that converts energy from one form to another
- Specifically, an ultrasound transducer converts electrical energy to mechanical (pressure / sound) energy and vice versa.

So, with that we will start with transducers. So, the idea is ok I want to generate the sound waves send it into the body and receive the sound waves ok. So, transducer is something that just converts energy from one form to other right, but in our case what do we want? I want to send pressure waves into the body ok. So, one of the way signal is the pressure waves and then the pressure wave gets reflected bounce back as we saw comes back and then you are recording it or you are detecting it with another.

So, you are recording it with the receiver right you are receiving it. So, again this is a pressure wave that is coming and hit, but as you know we would like to take the data and process it and display the image. So, we want to get into the electrical side of it ok. So, because then it is easy to handle the circuits read the signals, display it, amplify do whatever you want right.

So, the idea here is the signal that is interacting in the body is mechanical pressure wave, however, the signal that you are going to handle and process is going to be electrical. So, this transducer essentially does this conversion on one side you supply voltage it generates pressure wave, on the other side when the pressure wave hits you want to convert it to the electrical quantity ok.

So, typically this is scanner look alike and you will notice bunch of different transducers depending on the imaging study right. If they want to take abdomen scan for example, right you want to have the properties of being able to reach deep that is more important. Because usually you know abdomen region is its bulkier where you can also have some transrectal right. So, you can go through rfs and you can see inside or you have some here what you see is a linear array right.

So, maybe shallow organs breast imaging or msk right just muscle if you want to do that then depth is not that much compare to your abdomen that you want to do. So, you have different size and shape of this transducers, all of this are designed based on the physics of how you are able to generate the wave?

How does the wave interact with the medium and how you are able to receive and say what you got from where ok? So, these are not just for aesthetics or convenience, these are all designed such that you are able to get appreciable signal quality from different regions of interests ok.

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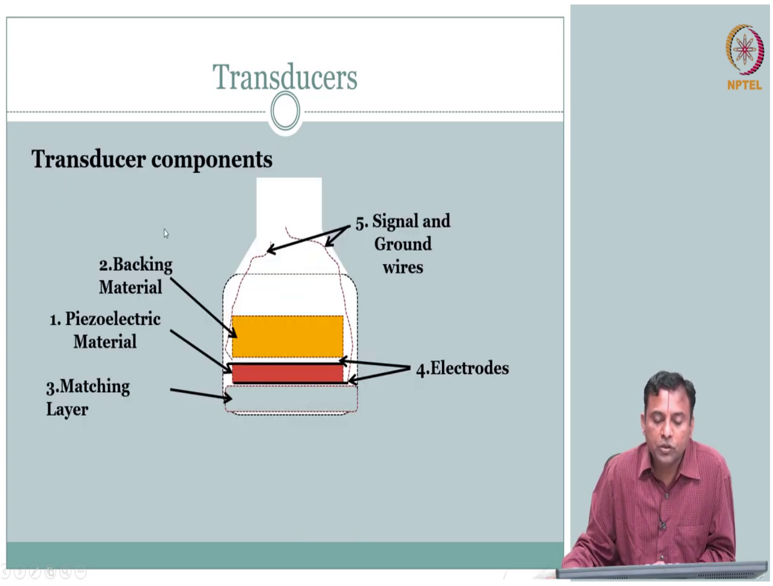

Transducers

Transducer components

1. Piezoelectric Material

2.Backing Material

3.Matching Layer

4.Electrodes

5. Signal and Ground wires

So, the transducer has several components major active component of interest is your piezoelectric material here, what does that do?

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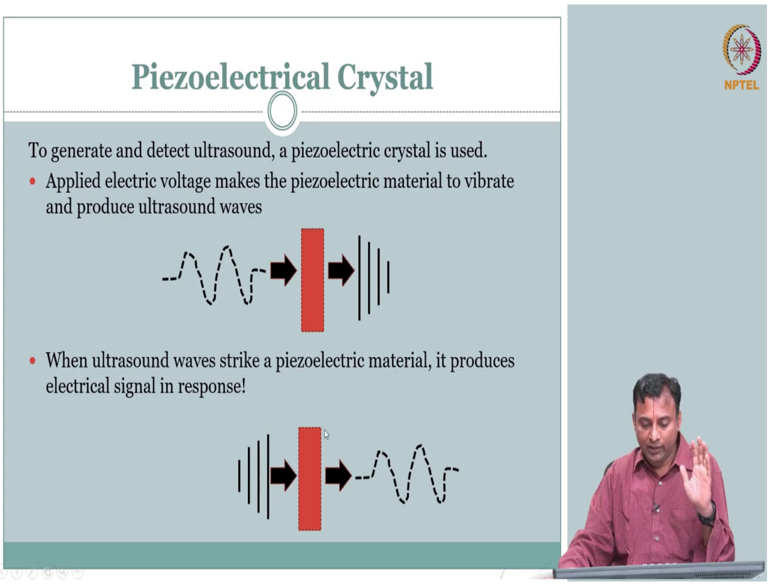

Piezoelectrical Crystal

To generate and detect ultrasound, a piezoelectric crystal is used.

- Applied electric voltage makes the piezoelectric material to vibrate and produce ultrasound waves
- When ultrasound waves strike a piezoelectric material, it produces electrical signal in response!

The piezoelectric material generates ultrasound and also right, generate and detect ultrasound. So, the advantage here is this material can act both as generating the ultrasound, so it can be used in transmit and also receiving ok. So, that is the idea about this piezoelectric crystal which is why it is very powerful. So, you could have the same crystal act as both transmit and receive ok.

So, when you have voltage it provides vibration and it provides ultrasound waves right. So, you supply electrical voltage to this crystal, it starts to vibrate and you create a pressure wave in the reverse when you have a pressure wave that is hitting it will create a voltage ok. So, this is very important lot of material property, material sense goes towards engineering this of course, our spirit here is to just understand ok.

This transducer is able to generate an ultrasound wave and receive an ultrasound wave or it converts pressure wave to electrical quantity electrical quantity to pressure wave ok, how does material is engineered to do that is not part of this introductory level.

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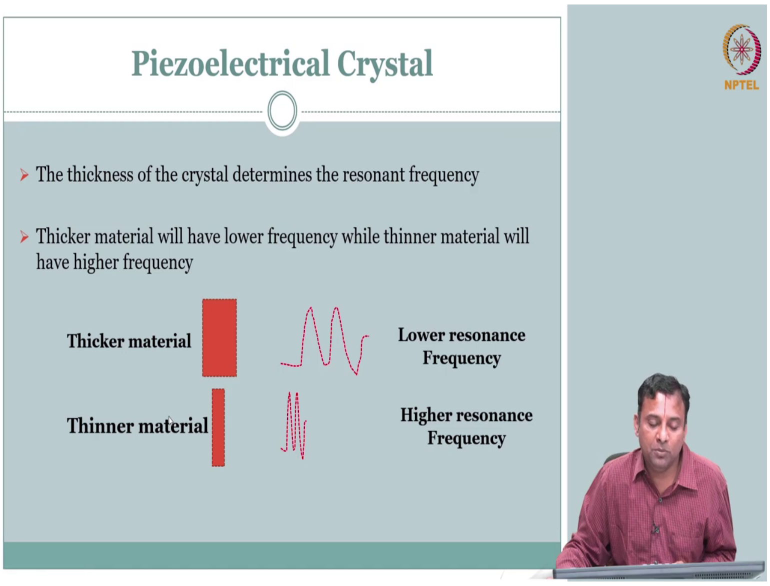

Piezoelectrical Crystal

- The thickness of the crystal determines the resonant frequency
- Thicker material will have lower frequency while thinner material will have higher frequency

So, at the first level we talked about size and shape just to give a feeling for that, so the thickness of the material right. So, we want material and we are interested in only one kind of wave what is that, compressional wave. So, we want the material to do only this. So, that the pressure wave is compressional plane waves that we talked about right. So, compressional waves is what we want.

And so depending on the frequency of interest right thicker material will usually give you a lower frequency thinner material will give a higher frequency. So, you notice when you go higher frequency if you want to generate higher frequency waves then the material becomes thin, the crystal becomes thin. And therefore, you know from a material point of view it becomes challenging because it is thin right. So, it will be brittle it can break. So, you have to and then you have to make sure that it has to be cut to size different shapes that we want, so all that becomes complicated ok.

So, the higher the frequency the manufacturing of these crystals becomes little tricky ok. But we know something what is this frequency related to oh frequency relates your lambda right some c and then lambda and we already passingly mentioned this lambda is a important parameter right. You want the wave length related to resolution. So, higher the frequency lower will be the lambda and so better will be the resolution, but then you notice the challenge also is coming.

So, we will just identify that and leave it at that because we are not going to go into the depth of how to you know engineer this material.

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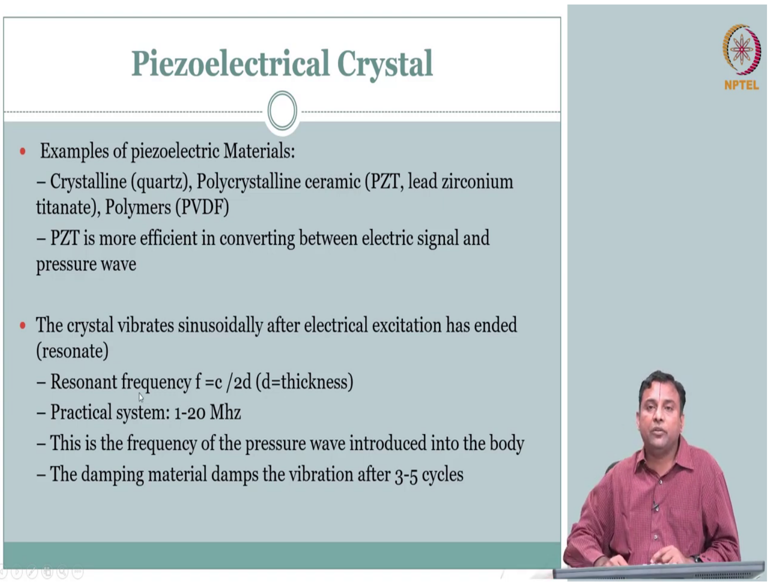

Piezoelectrical Crystal

- Examples of piezoelectric Materials:
  - Crystalline (quartz), Polycrystalline ceramic (PZT, lead zirconium titanate), Polymers (PVDF)
  - PZT is more efficient in converting between electric signal and pressure wave
- The crystal vibrates sinusoidally after electrical excitation has ended (resonate)
  - Resonant frequency f =c /2d (d=thickness)
  - Practical system: 1-20 Mhz
  - This is the frequency of the pressure wave introduced into the body
  - The damping material damps the vibration after 3-5 cycles

So, you have several different materials available by far PZT right is one that is used, you have PVDF polyvinylidene difluoride, but then that is a very sensitive material. And so usually what happens is this is used for calibrating transducers that are used in clinical application ok. So, PZT is more efficient in converting. So, this conversion efficiency is important therefore, PZT is kind of popularly used.

So, some of the key terms when you talk about transducer that you will encounter is this resonant frequency, what is this resonant frequency? Oh if you excite you have the best frequency right your frequency response will be high at certain frequency, what is that? That is your resonant frequency which is c by 2 d, d is the thickness. So, now you kind of see the we said thicker the crystal smaller is the frequency. So, this is like a connecting relation f is equal to c by 2 d. Of course, this has to do with the mode of propagation the crystal the stress strain of this crystal all that we are not really going in depth ok.

So, we have engineered this crystal predominantly to do only this vibration in one mode which is your thickness mode. And therefore, your resonant frequency can be specified by changing the thickness of the crystal. So, practical systems you get in this range of 1 to 20 megahertz of course, you really do not just introduce this, we will usually damp it. So, that you have about 3 to 5 cycles that go in ok. So, this is the pressure wave that is introduced into the body.

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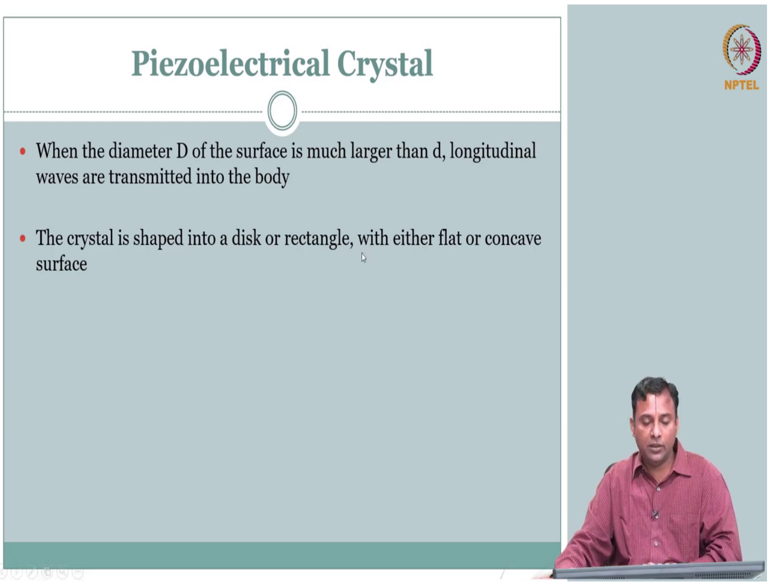

Piezoelectrical Crystal

- When the diameter D of the surface is much larger than d, longitudinal waves are transmitted into the body
- The crystal is shaped into a disk or rectangle, with either flat or concave surface

So, what is our objective our objective is to create this plane waves that we talked about right you want. So, when you have this dimension, so thickness is 1 dimension, what is the other dimension the size right? So, thickness is 1 dimension the other dimension is your say for example, if thickness if you call it in z direction because that is how we have been using then your xy is the other dimension. So, when diameter D right of the surface is much larger than your d that is your surface area is more than your thickness right, longitudinal waves are transmitted into the body.

So, these are kind of engineering the crystal. So, that you predominantly get a compressional wave that can be sent into the body this wave has to be sent into the body. So, the condition in which, so you can cut this crystal thickness is one direction, the other dimensions you can cut it to a disk or a rectangle it can be a circular or a rectangular right. You can have either a flat surface or concave surfaces we will talk about that as we go along.

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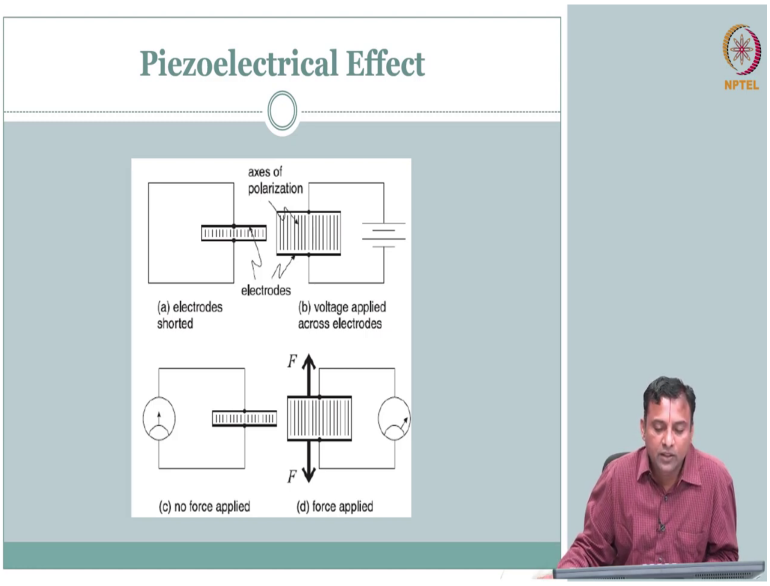
Piezoelectrical Effect

So, essentially what you have is you apply electrodes right you applied electric you get displacements. So, this is very routinely used this piezoelectric effect is routinely used in different fields right in different applications, but we will consider it from our frequency range that is of interest here which is going to be in megahertz. So, we will just appreciate that this is a good cryst, that this crystal is you know providing us with the ability to generate the compressional wave of a desirable frequency.

And also has the ability to detect this compressional wave and convert it to electrical signal with a reasonable efficiency right. The conversion loss from one form to other is still not too much that it makes it useless ok.

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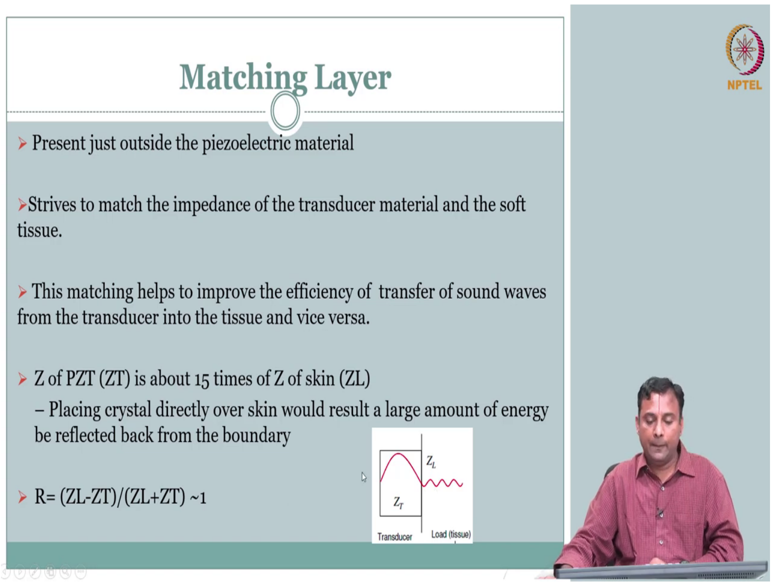

Matching Layer

- Present just outside the piezoelectric material
- Strives to match the impedance of the transducer material and the soft tissue.
- This matching helps to improve the efficiency of transfer of sound waves from the transducer into the tissue and vice versa.
- Z of PZT (ZT) is about 15 times of Z of skin (ZL)
  - Placing crystal directly over skin would result a large amount of energy be reflected back from the boundary
- R= (ZL-ZT)/(ZL+ZT) ~1

So, we will do that ok crystal was there is one another that was there in front just outside the crystal we saw what is called as matching layer. So, here we kind of talked about this little bit. So, the crystal is going to generate the wave right, how do we send it into the body?

Remember we talked about when you have to send it into the body if there is air here we talked about impedance mismatch.

So, first thing is the crystal can generate, but what is generated has to come out right. So, what you have is called as a matching layer what does it match, remember impedance. So, it has to match the impedance. So, this matching helps in efficient transfer of sound waves from the transducer into the tissue that is when you transmit. It is also true the other way right when the sound is getting reflected from inside the organs and it comes back it has to leave the skin. If air is there it would not leave the skin it will have it will go back in right.

So, you need this matching layer to reduce the impedance mismatch ok. So, your PZT, so Z here is your impedance right not the is zirconium Z that you have here. So, Z is about 15 times of Z of skin. So, naturally you know placing the crystal directly over skin would result in large reflection ok. So, we will not, so you need a matching layer for that. In fact, after having the matching layer also we talked about putting a gel and then placing it ok.

So, that is to really make sure that you are matched and you have sent out the trace of air that may come between the matching layer surface and the skin surface you do not want air to come in that layer ok. So, we put gel on top of this matching layer ok. So, you have your transducer this is your tissue and so you need to have in between them you need to have some matching ok. So, that it goes efficiently into the tissue otherwise everything will come back ok.

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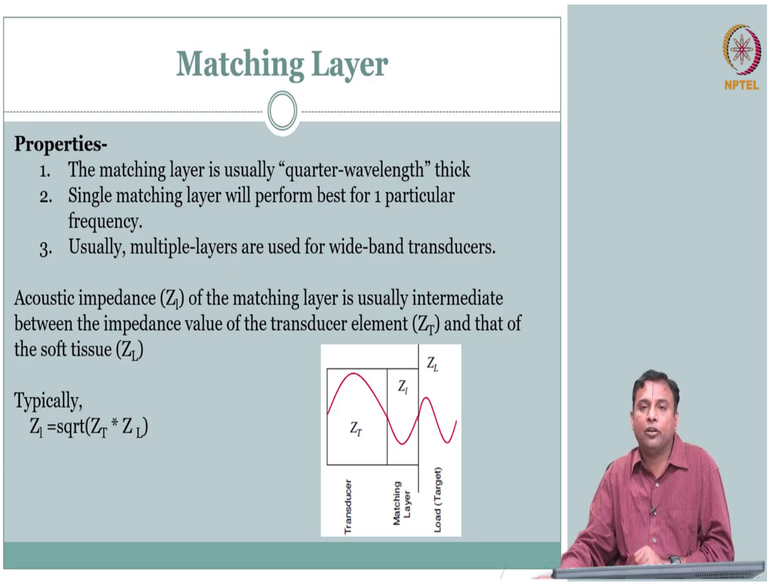

Matching Layer

Properties-

1. The matching layer is usually "quarter-wavelength" thick
2. Single matching layer will perform best for 1 particular frequency.
3. Usually, multiple-layers are used for wide-band transducers.

Acoustic impedance (Z_l) of the matching layer is usually intermediate between the impedance value of the transducer element (Z_T) and that of the soft tissue (Z_L)

Typically,

Z_l =sqrt(Z_T * Z_L)

So, this matching layer is usually a quarter wavelength and of course, we talked about you know this a distance right thickness related to frequency. So, clearly this matching layer also when you say quarter wave length that means, you if you have one frequency you have one wave length. So, it is probably efficient only for that particular frequency.

In reality you know we have wide bandwidth signals. So, you may have multiple layers ok. So, when you have multiple layers they engineer the Z effective right you have multiple layers matching layer. So, you kind of match it and they have some design constraint. So, you can get your effective to be square root of what is your tissue impedance and layer ok.

So, again these are engineering the matching layer which we will go little light. We will assume that ok there is a material science you have to adjust the impedances and so materials manufacturing that it has a lot of role in this part of the instrumentation ok.

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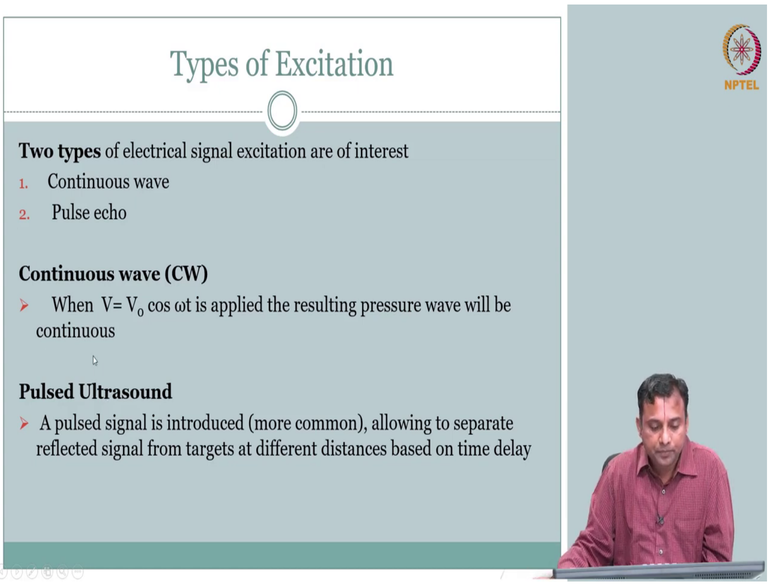

Types of Excitation

Two types of electrical signal excitation are of interest

1. Continuous wave
2. Pulse echo

Continuous wave (CW)

- When $V = V_0 \cos \omega t$ is applied the resulting pressure wave will be continuous

Pulsed Ultrasound

- A pulsed signal is introduced (more common), allowing to separate reflected signal from targets at different distances based on time delay

So, then we talked about converting. So, how there were electrodes if you see right there was a crystal you had matching layer and then there were electrodes. So, electrical signals of interest right, how do you excite it? So, you can do two ways you can get continuous wave or pulse echo two operations are possible meaning you can continuously excite.

So, if you apply a V which is continuous right V naught cos omega t. So, you are applying it at a frequency that is the resonant frequency of the crystal. So, you know the thickness. So, you know the resonant frequency. So, the efficient conversion happens when you apply a frequency that is what a resonant frequency. So, if I apply V as V naught cos omega t then the pressure wave will also be continuous that is one way of operating. But predominantly all of the imaging scanners that you will see actually work based on pulsed ultrasound ok, what is pulsed ultrasound?

I just apply you know a cosine right, that is we already saw. We apply a particular frequency of few cycles a pulse signal is introduced allowing to separate reflected signal from targets. So, the idea here is this instead of continuously applying I will send a shot burst right. I will apply a a sinusoid for a short duration.

So, that is why we called as pulse a small right two three cycles of a sinusoid I will hit then what happens this pulse goes inside the tissue it gets bounced back as we saw right reflection, refraction and then your scattering all that happens.

So, some amount comes back when it comes back it is hitting your crystal right matching layer and then your crystal. So, when that happens that is converted to your electrical signal. So, you apply a pulse and then the pulse goes into the medium it comes back. So, based on when you sent the pulse and when you receive the pulses right when and how much you receive the pulse you can comment about where the boundary is.

Because I know the velocity right if I assume my velocity in the medium I know when I am sending it when I am receiving it. So, if I know the time and I know that velocity I can locate my distance right. So, essentially time of flight calculations can be done, so pulsed ultrasound pulse echo. So, you send a pulse receive the echo of that pulse this is the most predominant usage for ultrasound imaging pulse echo scanning ok.

So, going forward we will focus more on the pulsed ultrasound. We will just leave continuous wave as is now. I mean some of a typical applications that you will see that we saw Doppler for example, right, so you do this. If you have gone for if you have gone or had a chance to go with somebody else you would have when they are pregnant when they go for a checkup right. They will have a instrument which is a ultrasound instrument they you know move it around the tummy and suddenly the fetal right if it is pumping. So, you could start to here.

So, essentially what happens is it is a continuous wave they move around and because of the Doppler principle you hear a shifted Doppler frequency it turns out that the Doppler shift is in the audible range and therefore, they use that. So, continuous wave is used useful, but predominantly for imaging purpose we use pulsed mode ok.

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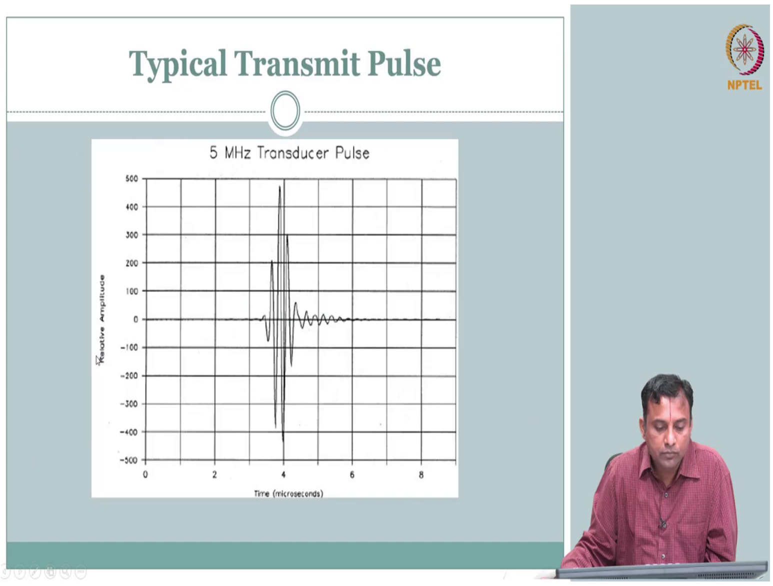

Typical Transmit Pulse

So, when we talk about transmit pulse this is a typical transmit pulse shape that you have, so 5 megahertz transducer pulse. So, this is what is created this wave form this pulse is what is sent into the body ok. So, a shot burst a few milli 2 few microseconds length here right. So, this is what is sent into the body and then you start to listen to the echoes and the problem proposition is simple based on the echoes how much I am getting can I say where is that interface, where is that scatterer ok.

So, in some sense its very simple I send a pulse in I get a echo back based on the echo and this information of when I sent it and how much and where I how much and after how long I am receiving the echo. I have to say where is that r look where is that reflectivity that scatterer right where is that or the interface where is that ok.

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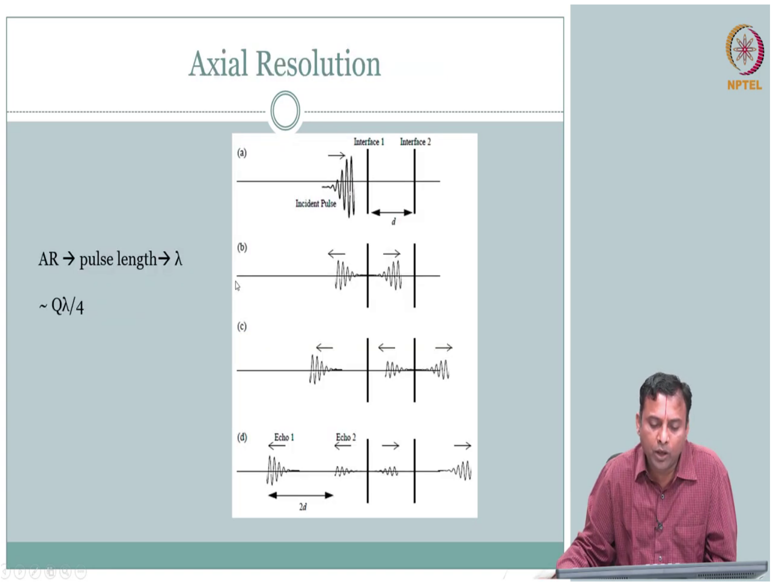

Axial Resolution

AR → pulse length→ λ

~ Qλ/4

So, that is your transmit pulse one important aspect here like we keep saying in we will kind of recognize it here as well because we talked about this pulse remember we already talked about this lambda and I said it is related to the resolution. So, in here what is your resolution? Resolution is the ability to resolve two things, in our case what is this two oh specially separated interfaces right.

So, I have two interfaces can I separate using this pulse, the two interfaces as being two different separated by a a distance right. What is the minimum distance that you should have.

So, that this pulse I can tease out from the pulse that the echo 1 is from interface 1 echo 2 is from interface 2 ok. So, clearly you have this pulse it is getting reflected right this is echo 1 it is getting reflected this is your echo 2 of course, echo 1 and echo 2 are separated in time because the interfaces are separated in distance right.

So, if you do that you are receiving this echo. So, now, your objective is from this received echo wave form which you get continuously with the time right you have to say whether these two are coming from through two different interfaces.

So, clearly you can see that this ability to resolve these two interfaces depends on the length of this echo the length of this pulse that you are sending right. So, pulse length your axial resolution in ultrasound axial or the direction along the depth right, your compressional wave the wave propagation direction that is called as axial.

So, pulse length directly is dependent on your resolution is directly dependent on your pulse length, which you can at the limit you can think about sending a pulse only one cycle. So, your lambda, so typically it is Q lambda by 4, Q essentially you can consider that as a quality factor that determines your shape right that incorporates your shape ok. So, now you see vividly that when you use pulse ultrasound pulse echo paradigm this wave length is a big deal that determines your resolution axial resolution ok. So, let us move on, let us move on.

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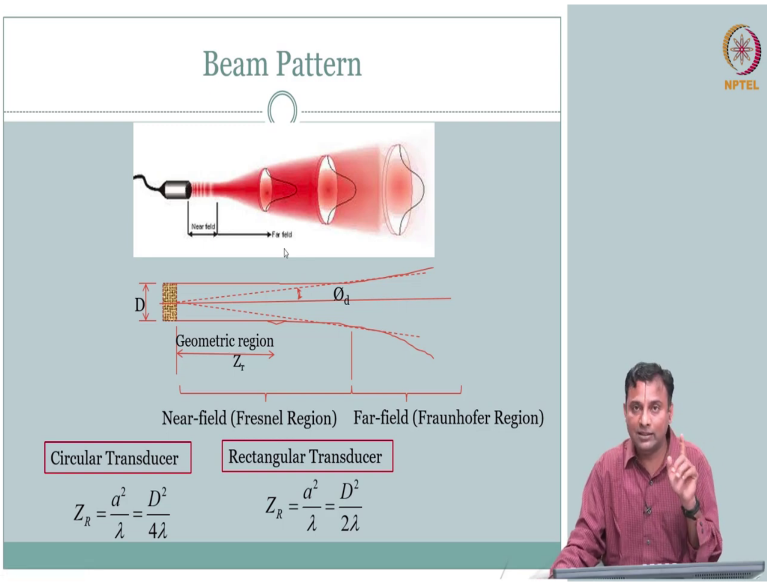

Beam Pattern

Near-field (Fresnel Region) Far-field (Fraunhofer Region)

Circular Transducer

$$Z_R = \frac{a^2}{\lambda} = \frac{D^2}{4\lambda}$$

Rectangular Transducer

$$Z_R = \frac{a^2}{\lambda} = \frac{D^2}{2\lambda}$$

So, now, what we want to do is in a simplistic term, what we said is ok, I have my transducer my transducer can create a plane wave and even more specifically we said we will create a a pulse and send it into the body. Next the question is oh I already know what happens if a pressure wave right the plane wave that we already talked about goes into the body it goes through reflection diffraction scattering ok.

So, now, the question is there anything more that we need to understand because we are creating these pressure waves right, we are creating using this transducer right. Is there any detail can I get my plane waves to be exactly you know along the plane right. Along the plane wave front every location we had the same pressure right that is why we called this plane wave front, is it really true right is it really true? Meaning, when I create this is the pressure changing at the center as you move along the side right.

You have 0 comma 0 is the same pressure there at the lateral edge in the other lateral ledge right is it same is a truly a plane right. So, it turns out that it is not as simple. So, we call it as beam pattern because you will realize that it is not a straight forward visualization. So, what happens is when you use this transducer right, when you try to operate it in the compressional the thickness mode right. When it is trying to do this it turns out that the wave that is coming out is actually inherently diverging in nature.

So, it is not just going to be restricted to only the various in some sense very similar we talked about X ray tube inherently it comes as a cone shape right. So, here also if you notice even though we have engineered the transducer, so that it is predominantly doing this, the moment it comes outside the transducer inherent nature is for it to diverge ok.

So, now the question is that means, the pressure wave when it is diverging the intensity is going to be different, whether you are situated along the centre or you are moving away from the centre. Of course, the pressure is also going to change with the distance that we kind of saw p of Z right, that is how we wrote p of Z comma t, but that part is fine, but in the other direction right in the x y right when it is going. So, the Z direction we already saw it is changing pressure is changing with the distance, but even that is not straightforward as we will see.

So, essentially what we have is we need to understand. So, the objective is this I am sending the sound wave, I get an echo based on the echo I have to say right, what interface is there at which location? So, based on the amount of echo the amount of echo is proportional to your impedance mismatch right. So, based on the amount of echo can I say that it at this location this is the impedance mismatch or more specifically this is impedance mismatch occurs at such a location.

So, clearly if I do not I want only along Z right that is one thing, but we are interested in imaging right. So, not only we should be able to locate in depth we should also be able to locate in the azimuthal. That is only we get an image right, if you look at the image typically you have a depth direction. So, skin will be at the top you have a depth and then you have the lateral width. So, if I pay attention what we have done is p of Z comma t Z is only depth direction, but I want to do imaging.

So, I want to not only say that oh there is a obstruction there is a object situated at 5 centimeters from the skin that alone is not sufficient. I should be able to say oh it is situated 5 centimeters from skin and 4 millimeters to the left of the centre, I should be able to say that right. In that context the transducer is generating the pressure wave, but then it is generating this 3 dimensional wave right it has a it and it is also spreading.

So, now the question is how do I describe this beam pattern? How do I capture this beam pattern? Because once I can capture what pressure is going, what is the pressure distribution then I know what I am going to get what I am going to get is this pressure into the reflectivity right. That is what I am going to get back your r reflection coefficient incident times the reflection coefficient is what you are going to get. So, what is incident?

Right it is not one, so the incident could be a change it could change over the area it could change over the volume. So, we need to be describing that. So, in order to do that at the first level roughly this is what you see there is a geometric region. So, depends on, so there are key terms that we will encounter. So, what we will have what is called as near field or Fresnel region. So, essentially what it is you have your thickness mode right of your crystal it is sending out pressure wave it is doing this, but then after some distance it starts to spread out widen right.

So, the region over which it is still holding on right is your geometric region which is your and then you have what is called as near field near to the transducer, you can clearly see the ideas is the further you go from the transducer more diverging it becomes. So, how much, so some context of whether you are near to the transducer or far a far away from the transducer is having an effect on the pressure field that each location is going to experience. So, you can see here there is lot of fluctuations. So, in the near field you can see there is lot of fluctuation, but it is not wider than your transducer width.

Whereas when you go far field far away from the transducer you see the intensity is smoother right it more near the centre as you go away from the centre it is the intensity of the pressure is reducing right, but it is wider it becomes wider region ok. So, there are the behavior of the beam is different whether it is close to the transducer or which is near field Fresnel region or Fraunhofer region or far field.

So, also it depends on the type the shape of the crystal the thickness controls the frequency the shape controls your beam pattern. So, if it is a circular transducer it turns out that you can retain this geometry right you can geometric region can maintain as D square by 4 lambda. So, it can retain before the divergence kicks in before the width is greater than your D right this is that length over which Z is your this direction right Z is this direction.

So, depth over which you can have this divergence less than your D your aperture size or your crystal dimension right that is your a square by lambda I mean D square by 4 lambda this is radius. So, ignore D is the diameter. So, D square by 4 lambda. So, if it is going to be rectangular geometry then you can have. So, rectangular transducer you can have D square by 2 lambda. So, the textbook goes on to deal with rectangular transducer right what we will do is we will now kind of orient ourself relate back to the text book chapter on imaging.

So, the chapter on instrumentation we started with the instrumentation, but then this is probably a point where we understood the transducer, transducer is going to create this wave, but when you create this ultrasound wave when it comes out it is not going to be nice well behaved just wave which is going in one you know only along the depth, it is going to spread out.

So, now we will talk about how it spreads out and what happens to the wave when you use this transducer. Then we will come back to ok now I understand the wave how it diverges. So, what happens if that hits my scatterer. So, my object that is a distribution of reflectivity what is the echo I am getting. And therefore, our imaging equation and image reconstruction that part we will get ok.

So, we will stop here with the beam pattern we will continue further we have what is called as width right this is. So, you have one direction along Z which is your direction of depth we talked about axial resolution. So, what is the importance or why is it important to understand this beam that is spreading out or the beam width in the other direction because we are interested in imaging right, we want to do imaging.

That means along the depth you would be able to separate two interfaces as we saw using the axial resolution capability, but then what about two objects that are in the lateral direction right along the width, how do you separate? Oh now you see that there is to be the idea is this is spreading out if this is spreading out, then there is going to be a challenge in saying right the lateral direction how two objects can come close together. So, the idea of axial resolution is related to the pulse length.

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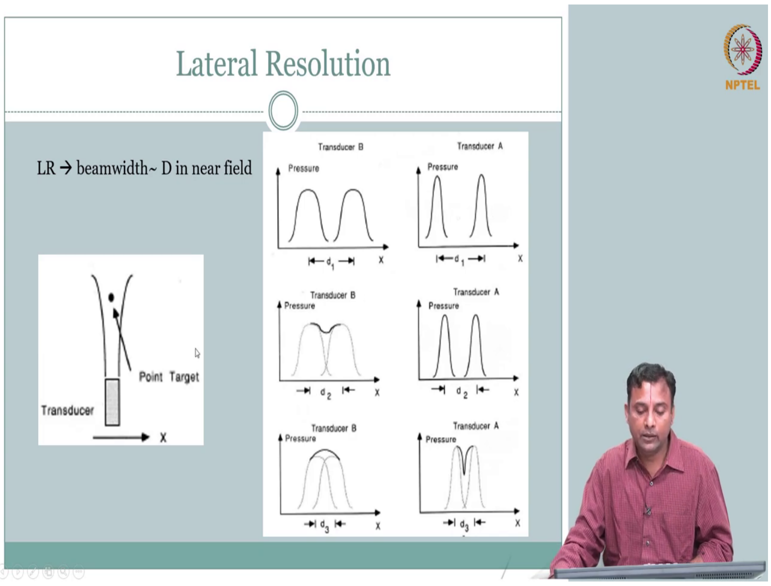

Lateral Resolution

LR → beamwidth~ D in near field

But the idea of lateral resolution is going to be dictated by your beam width ok. So, lateral resolution is roughly equal to your beam width which is the in the near field like we saw before it starts to diverge your dimension D is there so ok. So, when you have a transducer and you want to do an imaging you are going to this is only one direction depth direction. So, I should be able to move it in the other direction right only then I can get an image ok. So, X comma Z I can get my image plane as X comma Z for example, in the based on the X that is written here right.

So, if this is the case then I need to what I need to have as narrow a beam as possible right, only then when I move in X direction I can have good resolution. So, the idea about this beam width right. So, you have pressure this is in the lateral direction X direction. So, if I have 2 transducers notice here the right one is able to resolve better because its beam with beam spread is less.

So, beam width is an important parameter. So, when you come close together this starts to blend in here you completely lose in the lateral direction right. Whereas, in transducer A right some example A which has less spread the beam width is less right. So, here right this is what we are plotting. So, beam width when it is a narrow beam right, then the ability to separate in the lateral direction becomes better.

So, your lateral resolution is better. So, clearly you can see that the dimension of your aperture, D is what? D is your transducer aperture. So, your dimension of your aperture place a role in the lateral resolution, in the axial resolution it is the pulse length ok. So, therefore, it becomes very important to understand about this beam width. So, beam pattern we want to understand how we can shape the beam, so that it can have as narrow a beam width as possible ok.

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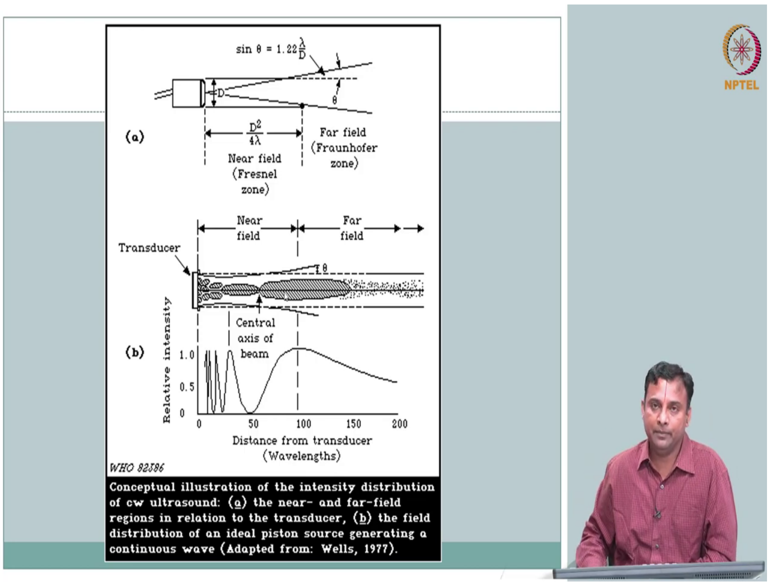

Conceptual illustration of the intensity distribution of cw ultrasound: (a) the near- and far-field regions in relation to the transducer, (b) the field distribution of an ideal piston source generating a continuous wave (Adapted from: Wells, 1977).

That is going to be your beam pattern just a overview slide. So, ideally speaking we said oh you will have the spread, but in reality if you have a you know view this is all the pressure intensity experience at different locations. So, this is your dept direction, this is your X direction if you will right. Notice the pressure distribution nothing close to what you would straightforward imagine right. We would have imagine plane wave front. So, everything in the plane is same and therefore, if I am this is my Z direction all the locations will experience same pressure, that is not the case.

If you are near field you get some weird intensities right where you are experiencing. So, this is why it is called as beam pattern. So, there is a pattern to it, in the sense that close there are lot more fluctuation. Whereas, when you move away you get lot more smoother right. So, the idea is we need to spend little more. So, depending on this beam pattern whether I send the pressure wave, when I send the pressure wave this is how it is going to insonify the region.

So, what I am going to get echo back is based on what is hitting at that location what the impedance mismatches right that is what I am going to get back. So, it is important that we understand what are the different beam patterns, how do we define this beam pattern? How do we get a handle on this beam pattern? If you get a handle on this beam pattern if I can tell the pressure distribution, how it is in space of the transmit pressure that you are sending.

Then we should be able to get an idea on the based on the receive signal I should be able to map out where the scatterers are located type and location of the scatterer ok. So, we will stop here we will talk about the idea of diffraction in the next episode.

Thank you.