Introduction to Biomedical Imaging Systems
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Lecture - 37
US_Imaging Equation_modes

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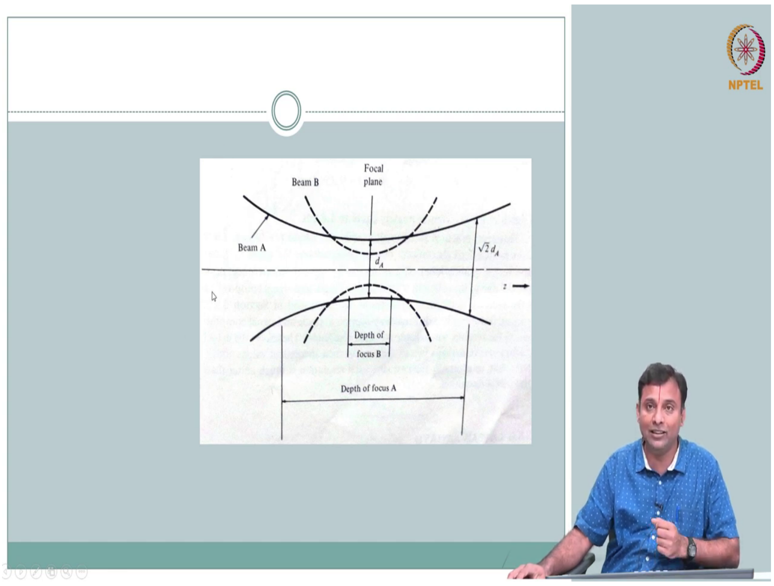

Ok. Welcome back. We are on to a very important aspect, right. In our format, we did the physics, we did the instrumentation, now we are all said to do the imaging. In fact, the way we covered in the instrumentation we have exclusively spend time only on the major active part which is your transducer, ok.

And even what we covered is only you know from a fundamental physics point of view. There is a lot more to do with engineering a transducer depending on the application, ok. But for now, what we will do is we will convince ourselves that at a introductory level, we know what a ultrasound transducer is, and it allows us to both generate a ultrasound wave and send it into the body, right because you have the matching layer, remember.

So, you send it into the body and whatever comes back it is able to receive, convert it into electrical quantity, ok. So, that much we covered. And in the physics part, we covered what happens to this wave and what happens to the wave interaction, the reflection you know transmission coefficient, reflection coefficient, refraction scattering, attenuation, all those interactions.

So, now in the image formation, right module we need to connect the instrumentation and of course, when we did the imaging equation, right we did not do it in our physics. Deliberately, I say it will be good to understand how the transducer the source, right, how is it generated, and how is it received, can we write our plane wave equation and how it interacts with the medium with r, depending on the size and shape of your transducer, ok. So, that is what we have covered.

So, now, what we need to do is how do we use this transducer, right; how do we use this transducer to send signal, receive signal, and using that how do we get a image of what parameter, right. This we covered, what parameter. So, in ultrasound we talked about, r reflection coefficient, right, reflectivity. So, essentially it is the impedance mismatches that are distributed.

So, you send the ultrasound wave into the body, it gets scattered, and you catch the scattering. So, we called it sending pulse, getting a echo of the pulse, that is how we wrote our imaging equation. So, now what we will do is expand on that imaging equation because we want to end up talking about an image, right.

Expand on that imaging equation, and highlight how we are able to put that together to form a image. Though that is what we will do here. So, the focus will be on carrying forward our imaging equation using this transducer. And of course, along the well appreciating the different aspects that we covered you know in with respect to say focusing, divergence, beam width, right all that, ok.

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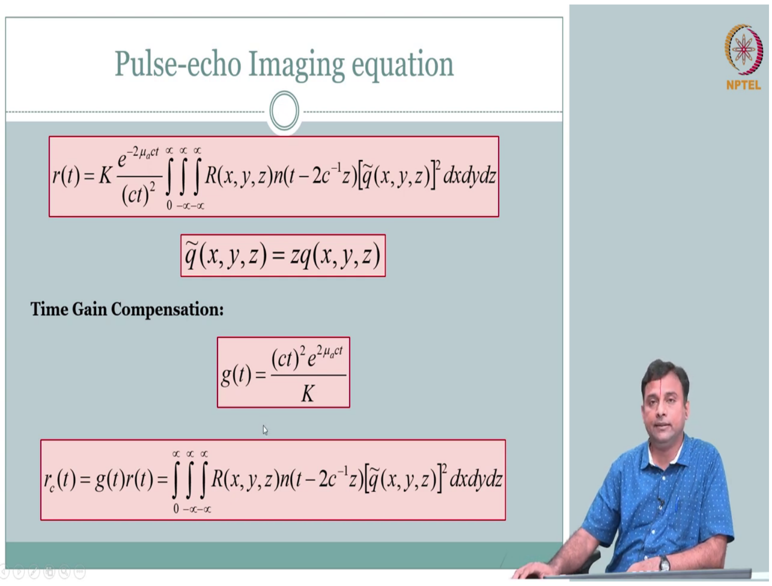

So, let us move on to write down the pulse echo imaging equation. Where do we start? We will start with exactly where we left off writing. So, we generated a pulse. So, we know how to write a narrow band pulse equation, right, that is what we started with. Envelope signal with high frequency, the resonant frequency centre frequency. So, that is where we started our imaging equation last time in the physics part of it, just after transducer, right.

So, we need to do that. So, we know that pulse. So, we got you know a triple integral, right in x, y, z, we wrote an equation. We will start with that, ok. So, this is exactly what we had derived. So, you send a pulse, that pulse goes, there is a point source, so the plane wave goes, it gets hit, scattered signal p s comes back, right.

And the amount that comes back is depending on the reflection coefficient, and then we said superposition theorem and then you come and hit on the surface, and then we had a everything is added on the surface, right whatever falls across the phase is added. So, we get our received signal as a function of t.

Why as a function of t? We will cover that little more. But the idea is whatever falls on the surface this is we called as x and y, z was your depth direction, right and whatever falls. So, you send plane wave, it gets scattered, whatever scattering is coming like spherical wave, that comes and falls. Whatever falls on this is net sum at a particular time.

So, t is related to your distance. We will make that little more explicit now, ok. So, all this is where we got so far. Of course, what was this q? We spent time. So, this q dashed, say q tilde here, so this is the same equation we had I have just made it q tilde with z of q of x, y, z. So, this q square I also said sometimes it is called as directivity function. In fact, we covered what this is in the Fresnel zone, Fraunhofer zone, near field, far field, we played with this q, right.

In fact, we told the far field it is essentially a Fourier transform of your transducer shape. So, if it is circular disc, then you get Bessel function, you get rectangular disc, right. Rectangular shape will give you sink in two-dimensions. So, this is your directivity we talked about main lobe, side lobe. So, this is your beam pattern if you will.

So, you send a signal, you send a signal, you get the echoes back and where all the signal the ultrasound wave is hitting after you send the send it out of the transducer, it depends on the beam pattern, right, near field, far field. So, wherever it is hitting, the location whatever is the reflection coefficient at that location that amount will come back, and you get a net sum. So, at every time point you have a signal and this is your signal that we talked about, ok.

But what is the nature of this signal? Ok, this is fine. But we know what we are sending in, right. This is the guy that we are sending in. What is it that we are sending in? We are sending a narrow pulse, right. You saw that it we drew the envelope and we had high frequency, the high frequency was the centre frequency and then there was this envelope signal that we plotted. So, the n of t, right, ok before we write down the n of t, we can make life simple by talking about ok all this constant that you have, right, is all a function of t.

Meaning, this is some factor you see this mu a ct. Mu a is what? Your attenuation. So, essentially signal loss. So, you have a signal loss, so this is all talking about the amplitudes, correction factors, and you know this is decaying with the time or in some sense. So, we what we can do is we know the signal that is coming from further time is going to be smaller because it is decayed. And so, you can give a compensation gain you can increase the gain.

How is that gain given? Time gain compensation. So, the further the time it takes to come back; that means, it is coming from a deeper location. So, you can use amplification and give a boost to the signal. So, this is called as your time gain compensation.

So, this is one of the in the instrumentation, after the, just after the transducer you get the electrical part you will have a amplifier which will do the time gain compensation. So, this is routinely provided. And you can have different functions, but usually you take, right, its linearly dropping with distance. So, you could give your gain accordingly, ok.

So, what we will do is to make it simple looking, we will say, we introduce a gain function which compensate for this, ok. And therefore, this can be provided. Usually this is given a see you have a potentiometer, you have a button that is given, right, you can adjust that. There will be slider buttons essentially because each depth they want to give.

So, there are several ways you know instrumentation they give. But essentially this is a implementable as a separate unit called as time gain compensation. In some places, this will also be referred to as depth dependent compensation, ok. And that is because time and depth are related as we will have a make it explicit now, ok.

So, that is your g of t. So, you can write your r of t, essentially as gain compensated, right g of t times r of t. So, this is your signal. So, what is this signal? This is receive signal. This is a complex signal, ok. So, you have your R of x comma y comma z and all other terms. So, this is a complex signal that you are receiving.

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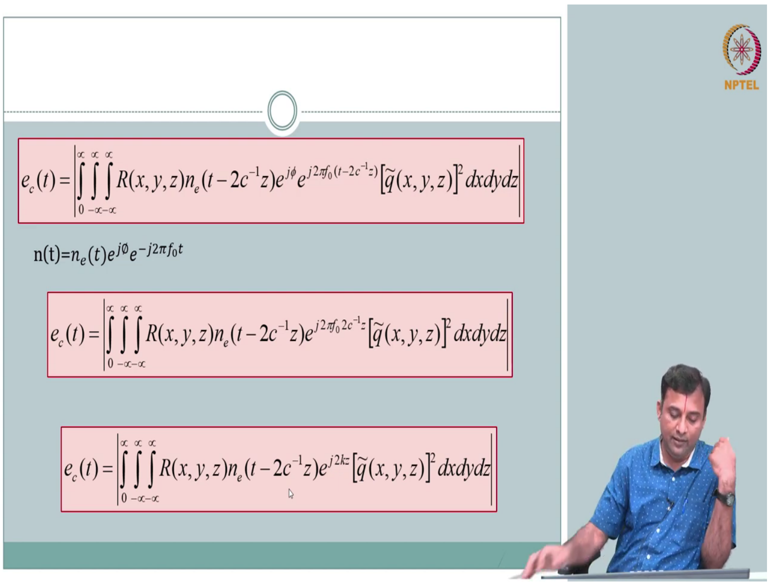

However, we know something about n, which is your narrow band, right. So, if you are talking about a complex signal, we can get your envelope of the signal, ok. So, you can write your envelope of the signal to be modulus of that, clear. So, what we have done here is modulus and we have recognized our n of t that we had is a complex, you know narrow pulse that we had, right. We could write it as n e of with e power j phi.

So, envelop of the signal and then your f naught which is your. So, go back look at the first, just after transducer, when we talked about signal, right we talked about sending a cosine pulse so on; some pulse which we also plotted the envelope. So, that is the pulse that is sent in, ok, narrow band pulse.

So, that time we wrote n of t is nothing but n e of, right you had a envelope of the signal with a phase and you had this f naught which is your high frequency. So, this is just brute force substituting that and this modulus gives you the because this is a complex signal, right, so this is give you the envelope, ok.

So, what is this? This is your signal pulse that you sent, the pulse getting echo back. So, this is your pulse echo envelop of that, ok. So, now, what do we need to do? Well, this is fine. This is essentially putting in all the details in that basic equation that we had, but we could do few other things essentially giving formality. So, you look at this t, right.

So, this is, I mean I just have it here if you have to go through the notes later. So, n of t, recall, this was from before. So, I have substituted for n of t as this guy, in from the previous slide. So, if you are looking at the previous slide. Coming to this slide, we have a modulus, so we covered this as envelope and then n of t is substituted to n e of because we recognize this signal. This is what we are dealing with. This is the pulse that we are sending in, ok.

So, now what do we do? Well, e c of t is modulus of R x, y, z, right, your envelope e j phi. Where is this e j phi gone? Not only that, look at here, right, 2 pi f naught t is not here. So, what have we done? We have recognized that you are taking modulus, right. So, if you have an exponential which is not varying with your, which is not a function of x, y, z, then that you do not have to worry about that, right, modulus of exponential function j power whatever it becomes one. So, you do not have to worry about that.

So, essentially from here to here, we have recognized that anything that is not function of x, y, z, right, the exponential you do not have to worry about that. So, you, e power j phi and e power j 2 pi f naught t is taken out, ok. So, you do not have to worry about that. So, you just are left with the remaining, ok.

So, this is your signal that you are receiving the envelop, right, because there is modulus, the envelope of the pulse echo signal, ok. Pulse you send, echo of that, this is the one that you are receiving. So, we could essentially do one more small change instead of writing this, right, you recognize this 2 pi f naught the c inverses 2 pi f naught by c. This we can write it in terms of k. Remember the wave number. So, the only difference between this equation and this equation is where we know our basic pulse echo signal, we are just writing it in terms of wave number k.

This becomes kind of convenient to interpret. We will do that. But this is your, right no big difference between this and this. So, now we are all set. We are all set to recognize what this is telling us, right. So, this is the data that you are going to record, you send the signal, you receive the signal. This is how, this is that received signal. Of course, this is the envelope of the received signal and the received signal encompasses your R, right because you whatever you sent in, getting you know reflected bounce back.

So, depending on the distribution of your R in x, y, z, along with you are sending a pulse, but that pulse is not going. So, the pulse has a divergence, it has near field, it behaves one way, far field it behaves another way. So, there is a distribution of the pressure pulse as it travels, that is what is captured here. So, this is the parent equation if you will. This is all in compassive, right.

So, what we can do is, ok if you have a transducer, you send this this is what you receive. Is there a simpler way to look at it? Meaning can we simplify this little bit to get a little more intuitive feeling about what is happening, ok. So, beware this is what we are going to do for scanning.

So, this is at one location, right, this is at one location. So, we do couple of things e c of t, we send the transducer, you receive the transducer, we got this. But what we have not recognized so far is transducer is sitting at one location, right. We have not really talked about that. We have just said this is the echo received by the transducer as a function of t. But if you have to scan, right, if you want, then you need to have x, y, z. You get only z here; e c is a function of time, which probably is related to the depth which we will find less now.

But the idea is we do not have a location for where the transducer is sitting because that is where the pulse is sent and received, ok. So, when we do scanning, so this is fine, but if we are in imaging business, we need to have location where is it, right, where is it in x, y, z, the signal that you are receiving.

So, signal that you are sending, signal that you are receiving happens to be same location because it is the location of the transducer that is the acting as both the transmit and receive, ok. So, we need to make this little more amenable to carry forward for imaging or describing a image location.

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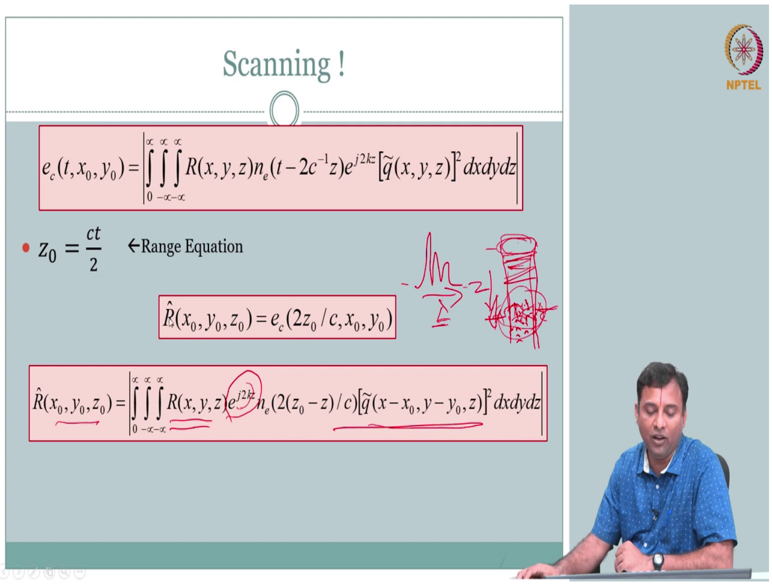

So, what we will do is we recognize, we have to do scanning, and therefore, we will start to identify. We will write our echo signal received, not just as a function of t, right. It is actually located at some x naught at y naught. So, remember the x y plane, z is your depth, ok.

So, now, you have your e c, is recorded at the transducer surface which is located at x naught at y naught, x naught y naught and as a function of t. So, clearly from here you recognize. This is fine. But why t? Is there a relationship between t and position? More so, you recognize what is this t, I send the pulse, I receive the echo from after some t equal time t. This is what this says.

So, what I can recognize here is this is time. So, something is travelling and we know the medium velocity c. So, I send the pulse, if you assume a short pulse then it is reasonable to assume that you send the pulse, it goes at some velocity c, it comes back. So, it has travelled, one distance, second distance, so it has travelled two distances in this time interval. I know the speed, right.

So, you can write your z naught, right is nothing, but ct by 2 because I have travelled two times the distance in the captured time interval with the velocity c. So, this is your velocity, this is your time. So, velocity into time gives distance. But this distance is two times because the pulse is going, the echo is coming. So, you are recording only the echo, so that means, it has taken the pulse to travel one distance and the echo to travel the same distance. So, it is a factor of 2. This is a very important equation which is called as range equation, ok.

So, this is important because any time you record a echo of a sound, you have to account for the time for the signal to go till the location which is going to give you the echo back, ok. So, it is one distance. Second distance it has to travel back. So, there is a factor of 2, between the time it takes and the distance, ok. So, that has to be accounted for.

So, this is your z naught. So, essentially what we want to write is this e c is not just t comma x by, this t is actually I know, right. I can write it in terms of z naught, right. I can write this is a spatial quantity. I can write it as a spatial quantity. So, what I will do is, I will write my R hat is what? Usually estimate.

So, what you are estimating at x naught, y naught, z naught; that is your receive signal, right. So, you can see your received signal received 2 z naught by c comma x naught comma y naught at this location, whatever you are receiving is nothing but you call it as your R hat of x naught, y naught, z naught.

What does this mean? Going by our notion, this is your ground truth distribution of R, right. So, remember how we did this mu in X-ray based attenuation coefficient to X-ray energy or gamma energy. So, here what you are fundamentally doing in X-ray, I mean in ultrasound? You are trying to go after, you have some this, I send sound. I am a 3D distribution of acoustic impedance mismatches, right, different acoustic scatterers, distribution of acoustic scatterers each one having it is own impedance, acoustic impedance.

So, the density and compressibility of this acoustic scatterers, right that gives raise to your acoustic reflection coefficient, right, impedance which dictates your impedance mismatch dictates your R, correct. So, what you are estimating is nothing but this guy what you are measuring, what you are recording, the signal, is nothing, but an estimate of this R. Of course, there are other factors here, what you send, and how would how you sent, ok. But you get the big picture. The big picture is what you are recording is nothing, but an estimate of reflectivity or the scattering coefficients, ok.

So, we will write it in that form. So, R hat of x naught, y naught, z naught is you substitute at this, right. I have my n e, z naught minus z c and this directivity part, clear. So, it is unveiled usually that 3 integrals and other thing, so it looks complicated, but you actually you can see term by term, it all is intuitive you send a pulse and the pulse is going, right. It is going diverging. So, it has field pattern.

So, you have send a pulse, which is going through the field pattern. When it is going in hitting allocation whatever is the reflection coefficient there, R of x comma y. So, what goes in, hits that, reflection coefficient times that quantity is what is coming back, whatever is falling on the surface, right. You are integrating and you get a value. This we say is a estimate of this guy.

So, you can see that there is an influence of this R is a ground truth, but what you are doing is an estimate. So, there is an influence of the pulse you sent, the like the pulse length, and the shape of the pulse, and the field pattern. Both of them together, right have an influence on how this R is spoiled, like spread around, to get your estimate, right.

So, in some sense, in some sense, before we jump in, in some sense let us take you know big picture view some of the key terms, we will clarify here. So, what you see here is this field pattern, right. So, before we jump in and do imaging, you recognize in one transducer, right, the area of the transducer the x naught, y naught, right the shape that has an influence already here, right.

So, if you pretend that, ok this is all complex because we have talked about, near field, far field, if you want to ignore that, even if you want to ignore that and you pretend that we had a circular transducer, and it is sending only, right waves, plane waves of same intensity, right. This is my z direction, depth direction, right. So, the plane of the transducer is x y for example, right. So, this is the plane and is directly sending pressure wave in the z direction.

Even if you take like that, right that is a simplest case, so that I can avoid all this you know main lobe, side lobe, Bessel function, or sink function, you already notice it is a volume, a cylindrical volume, right it is a cylindrical, it is a cylinder. So, whatever is there inside that cylinder is going to get summed. So, ideally you want it to be as small as possible, right.

So, this, whatever is contribution by that because of this triple integral, we call this as a resolution cell. So, there is small volume, so you have to have as small volume, and within that you will have different scatterers, right. So, ideally, what you want is this has to be as narrow as possible, this beam has to be as narrow as possible.

But so, what happens is, then it goes small and small because your scatterers are much smaller than your lambda you have many of them, ok. So, this, so you have the ideal ground truth of distribution of point scatter, but how many of the scatterers fall within your volume, right. So, that is your resolution cell.

In z direction, you know the pulse, right. We said about 3, 3 cycles, 5 cycles. So, z direction this is what is your pressure pulse. So, likewise, you have your width direction, we talked about, right. If ideally, we just make a simple argument this is just cylinder, it is just retaining its direction, right. So, you have and then you have height direction as well.

So, put everything together, there is a resolution cell in terms of lambda, right. So, you have many of these scatterers inside this resolution cell. So, you want this cell to be as small as possible, so that you have better resolution. So, the signal that is coming, that you are recording is from a smallest region, right. That is what you want, so that you are able to resolve.

However, you notice that that is one important aspect. So, resolution cell that dictates which is in terms of lambda has an effect on resolution; so, how much can you make it in the axial direction and beam width in the lateral and elevational. All this dictate your resolution and it is not same, ok, in ultrasound it is not same. So, axial direction you have better resolution than your width and elevational width, ok.

And then you notice one another term here. What is that? That has again you have how many you know. So, you have this is a e power j k to k, this is, k is your wave number, z is your distance over which this pulse is, right. So, how many; so, you can notice that each of these scatterers is going to send out a spherical wave, right.

So, what you are going to get is a sum total of all the spherical waves that are coming up with this multiple scatterers that are there within a resolution volume. So, that means, by the time because of the small differences you have in distances at the scattering location, right, when it comes not all of them are in phases. So, some can be actually out of phase, so sometimes it will be in phase.

So, essentially what happens is you have this randomness, right because of this term, because where this can be holding, right. The number distribution of your scatterers within a resolution volume, that can dictate the statistics of the signal that you are receiving. So, typically we call this as speckle artifact.

So, you will see in an ultrasound image as we will show and also maybe you have seen it before, that you will have some texture black and white, it is not going to be smooth like your CT image or MRI. So, you will have some dark region, right cyst or hyperechoic region, but then the background you will see black and white, gray which are appears to be gray, but you see a texture, that is called as your speckle and that comes from this guy.

So, in the imaging equation what you record, it is influenced, you are always going to have some speckle effect, right because it all statistical distribution of your scatterers in the medium in relation to the size of the signal lambda, ok. So, that is going to have an influence. This is a big guy your beam pattern.

So, how; if I can make it as narrow as possible, then I can get better resolution. This we saw. We saw the effect of if you do that, then your depth of focus is reduced, the slide that we started before we started this topic today, right in this module. So, this in some sense is always what you are recording all this is inside, right you get net sum. Can we carefully decouple this and how do we improve the image is a trick, ok, requires lot of effort and engineering, ok.

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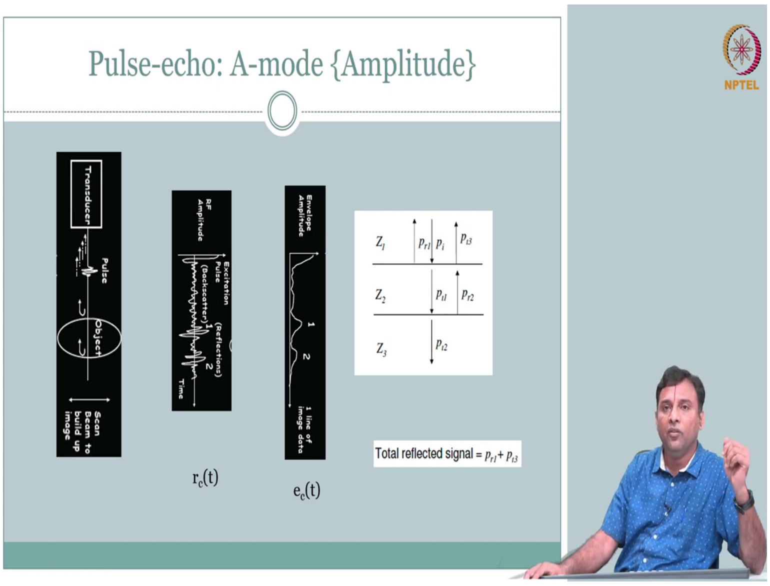

So, direct extension of this is what? Ok, I do the scanning, how do I want to do than image, right. So, before we do that what are the modes in which we can apply the use this transducer or rather, how is this knowledge of generating a pulse sending it, receiving it, getting the echo, how all has it been used. First is a pulse echo mode, usage, first usage is your amplitude mode.

What do we mean by amplitude mode? Straightforward, I send the pulse I am receiving the echo, right. What is the echo amplitude as a function of depth? Right, exactly the way we wrote the imaging equation. So, what is going to happen is I am sending the pulse with some amplitude, right. It encounters a interface impedance.

If you do not have a impedance mismatch, you are not going to get any echo back, right. There is no reflection coefficient is going to be 0, if you do not have any interface. So, you have your Z 1, Z 2, Z 3, all denoting different layers in this case. So, I send a pressure pulse p i incident pressure with an amplitude p. Some amount is reflected back, how much? That depends on the reflection coefficient, impedance mismatch.

So, you should be able to calculate all this because we covered what is that coefficient, if it is intensity what is it, if it is amplitude what is it, right. Z 2 minus Z 1 by Z 2 plus Z 1, if it is hitting at a angle, we had a cos theta term Z 1 by cos theta, so all that you should refresh from your physics. But the idea is when I send the pulse some amount comes back further goes down this p t, whatever is transmitted further in experiences are interacts with the next interface.

So, from this some amount goes back, right, reflection coefficient, transmission coefficient. So, whatever comes back here, some amount can get reflected some can go forward, clear. So, of course, this is just amplitude written as p. But what you have to have another factor is attenuation. This amplitude is reduced as you go with distance, right, depth.

So, you can also add that, ok. So, this can directly be used to assess where these interfaces are. See that is advantage. So, I can send the pulse, if I get an echo, then I know that there is an interface there. So, this allows me to, when I just listen to the echo wherever I get a dominant, right, when I get a good high amplitude echo back, I can then based on my range equation, I can say where which location that interface is present, right.

So, in some sense; so, your total reflected signal is your p r1 plus p t3, ok. For simplicity, usually we do not worry about this multiple reflections, but this can cause artifact we will not worry too much about it at this in this course level. But the idea is total reflected signal you could get from direct one echo or multiple echoes, right from.

So, what is the goal now? The goal is if you just plot this, right e of t was the thing, right, so we can plot this. So, you have a transducer, I send a pulse, the pulse goes through, it hits an object, some amount is reflected back, some amount goes further, some amount gets reflected back, some other goes further, right.

So, you see this is a sketch of this situation, right. So, the sum amount is getting back is your p z 1. So, if you add a material, so of course, here z 3 is written as different material, but you see the idea. You send, you get some back. If you just plot this, right that is your RF amplitude.

So, this is your just the receive signal which we also call as raw signal, not the envelope per say. This is just yours time trace, right. You get the signal, you send the signal, you start to receive the echoes. So, you have some small signals because there as material has some imperfections, right. So, scattering happens all the time.

So, you get some signal back, but major signal or major echo comes back at the interface. So, you get next interface, you get another signal, and then it goes. So, you can clearly look at this, right, time trace signal or your raw signal. You can look at, ok this is a pulse that you sent. I get the echo, first echo at some time t 1, I get a second echo at time t 2, so based on velocity, right and that time you can always calculate your z.

So, you can tell where is a location of your first echo, where is the location of your second echo, right simple signal processing, peak detection. Of course, we were talking about, this is your complex RF signal that you receive. We talked about envelope. So, what they do is you take the envelope of the signal, I have the first echo from here, second echo from here.

So, I can actually see this amplitude trace and tell where all there is a change in impedance, right. This is very powerful. If I have a crack in right I mean typically non-destructive evaluation they do for materials, right the same concept is used. I have layers. There is a layer where it is delaminated for example, or some glue is gone bonding or a crack is there, right. Then, only at that location you will get a huge echo. So, they have to find out where, right. So, similar things.

So, envelope amplitude signal, a mode is very useful. However, you notice that this is not two-dimensional yet. This is at one location I am sitting, only the depth width trace I am getting. But this itself is very powerful. Why? Because you can get the information about where all the acoustic impedance, there is huge mismatch. So, this tells me there is an interface here, tells me there is an interface here, right.

So, this is not routinely used in imaging, but there are locations application where this is. For example, retinal detachment, right in your eyes. I can do this. I can send it through my eyes. Keep the transducer outside the eye. I can send the wave. If there is retinal detachment, what happens? There the retina is slight detached, right. So, there is a different material. So, the acoustic impedance mismatch will be huge, right. So, you will get an echo.

So, now you understand. Sitting outside, I can detect if there is a detachment then I know I am going to get a strong echo from there, ok. So, can be used in that regard, right. My time sense is fine here, that is good enough. Of course, you can do this to get a whole area, I mean image plane, but even simple things amplitude mode is useful, ok.

What are the other modes that this can be used? Direct extension. So, this is your e c of t that we wrote down before, right. This is your e c of the t. So, this is your r signal, r c of t. This is the envelope of that signal. This is what we wrote in our imaging equation, ok.

So, now what happens? What are the other modes? A direct extension of this mode, right. Before we do that; direct. So, we can do a direct extension of this mode which is interesting because like I said this is not an image per say, like you do not have the second dimension it is only the depth dimension. But this can be the interesting extension of just this signal that you see in the interpretation can be made useful you know we will talk about that.

Just before that if you have to do imaging, right you have to send the signal, get the signal back from a different location, right only then you can build the image, right. Otherwise, this is just that one along one at one location x naught comma y naught, this is a function of z, right.

I want to move to some other location, and then again get another function of z, so that I can get a x z image plane or y z image plane, correct. So, we will. So, we will have to do that. So, let us just make sure that we have certain parameters that are of interest. We will cover that. So, that when we jump ahead to do the imaging, we know how to operate it.

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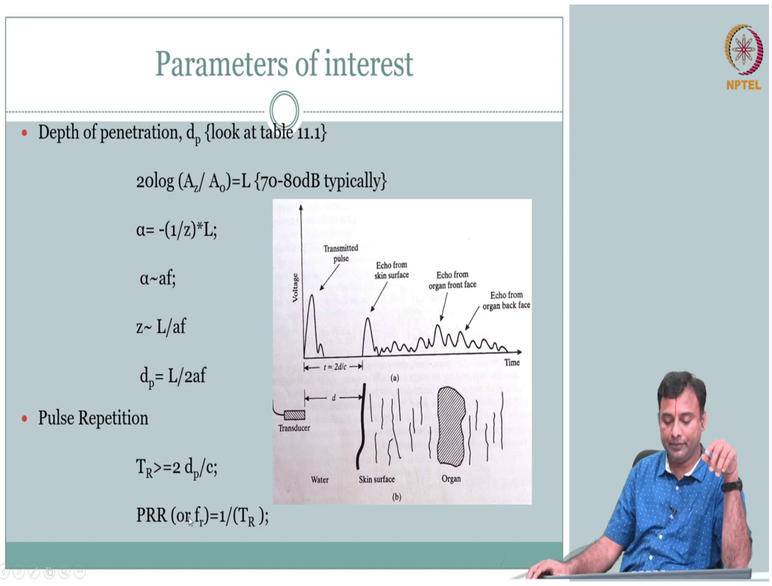

So, parameters of interest, essentially, we are talking about depth of penetration. So, I sent, I have my transducer, I have my skin surface, so there is this coupling gel or whatever you want to put, right. So, I this is my skin surface, there is some organ. So, this is your r c of t like your e c of t, right in the previous slide we have.

So, this is the envelop, right. Echo from the skin surface, echo from organ front, echo from organ back face and of course, there are several different interfaces that are there. So, you have some weak echoes. So, this is your receive signal, amplitude, right. So, now what are the things of interest.

First thing is depth of penetration. What is that? Why is that important? So, how long should I listen right? I can keep on listening because the wave is going and it is getting reflected and coming by echo is coming, but how long should I listen to the echo before I send the next pulse.

So, essentially, I told, right the idea is we want to go to a different location and start to send and receive the echo. So, how soon can I go to a next location? How long should I wait in the same location. This is a critical question. That we call as depth of penetration. Meaning how long you wait, right is going to be determined on how deep you want to get the echo from.

What is the challenge? The challenge is when you send the signal, the signal is attenuated as you go further, right. Absorption, scattering, reflection, all of this reduces your transmitted signal, right as we go at each interface. We know, the signal is reduced as you go with the depth, ok.

So, there should be some. And then we talked about gain, but there is a level to which you can give the gains. Beyond which, right beyond certain depth the signal is so weak that you are essentially at the noise flow. You are not able to amplify the signal preferentially. So, you will just amplify noise as well.

So, what is called as depth of penetration is the threshold that you set beyond which you believe the signal, the echo that you listen you cannot separate the real echo from a random artifact, a random background noise, ok. So, typically, right, typically most systems you are looking at a level of tolerance, right if 70 to 80 dB. So, until that time it can still recover the signal, the instrumentation can still the amplifier can still recover the signal. So, if it goes below 80 dB, then it becomes futile, ok.

So, your L, if you talk about L is your length over which, right, is a loss length over which some loss is happening and this loss is until 80 dB for example is recoverable. That is you can give the gain. So, this is your loss in dB which is nothing but A z. What is the A z? Amplitude at location z.

A 0 is your amplitude that you send of the pulse. So, A z can be going down 80 dB essentially. It can go so small until which you can recover. Anything beyond that, if A z reduces any further you will not be able to recover, then there is no point in listening to the echo that is a logic.

Why? Because you cannot recover anything. So, that is your depth of penetration. So, until the depth until which you think you can get the echo and make sense that this is echo and not echo from a interface and not just a noise. So, your loss, you remember this alpha that we talked about, coefficient, right, alpha is, remember alpha z is equal to the loss, right. Alpha is all coefficient into z is your alpha z. So, alpha equal to minus 1 by z times L, L is your threshold at which you are doing this.

So, you can write your alpha, you can assume it to be a we covered this absorption. So, this is your frequency dependent attenuation, right. We talked about alpha is af, ok, first order absorption f, right. So, it is depth to dependent. So, you therefore, we could write your z, right L by af. Of course, this, what is this z is approximately L by af. Yes, this is your distance, right, z is your distance thing. This L is the total loss, this is your loss per frequency per centimetre, right. That is what you go back and look at your definitions.

So, your alpha is what? Go back look at your definition, alpha was dB per centimetre per megahertz, if you if you go look at it, ok. So, your z is total loss divided by this af that is your depth. However, your z is fine, but your depth of penetration when we want to calculate you have to take for the transit time, right. We talked about this time of flight calculation your range equation.

So, your depth of penetration is L by 2 af because attenuation happens going one time and then coming back. So, this is your total loss, right. Because what do you say, receive signal, signal that you sent it is getting lost, and then coming back it is getting lost, e power minus alpha, we remember we wrote as e power minus 1 mu a, the 2 was again go, come back, same thing, right.

So, a depth of penetration if you want to calculate the depth of penetration, the total loss by 2 af this gives your depth of penetration. So, this is very important. So, for a certain scenario I can only image till so much depth, so that depends on your frequency as well, right. So, your because we talked about frequency, depth dependent frequency, when we talked about pulse axial resolution. Now, you notice depth of penetration is also a challenge.

So, if I want high resolution, axial resolution, you want to have a higher frequency, right. But if you want to have a higher frequency, my attenuation will be high and therefore, my depth of penetration will be low. So, that is why we see this different shapes and size of transducer when I talked about. So, if you want to do abdomen scanning, typically you want to see deeper like 10-15 centimetres. So, you will use a lower frequency. But if I want to do something superficial, right then I can go for a higher frequency.

So, like I said for i, right, i you are looking at very 1 centimetre kind of depth, right or even less. So, that is very small. And therefore, I can gain, right, if you believe the instrumentation is 80 dB is tolerant, then I could actually have very high frequency 20 megahertz, 30 megahertz, 50 megahertz, I can have.

Whereas, if I use 2 megahertz, if I have the same loss pretend the material property is same, then if I can go 1 centimetre with my 40 megahertz probe, right, I can perhaps go 8 times more, 8 centimetres for the same loss with a 5 megahertz probe, right. So, that is the difference.

So, depth of penetration, frequency, axial resolution, all of this are trading off, ok. One another thing that will trade off is if what is it, what does this depth of penetration mean. That means, I have to wait until so long, right, before I can send the next pulse. If I send the next pulse, I have to make sure that I have heard the most distant point that I want to hear.

So, that means, you have what is called as pulse repetition, when do you want to repeat the pulse, when do you want to send the next pulse out. This is important, right. Because now I said this is at one location, I want to move to do the scanning, so I need to know how long should I listen in one location before I move to my next location. And therefore, pulse repetition is an important.

Pulse repetition is going to depend on how deep you want. Of course, this is depth repetition is usually in time. So, we can always relate depth distance to time in terms of velocity, right. So, you can write your time for repetition is nothing, but 2 d p by c, c is your velocity.

Again, 2 times the depth you have to account for, that is go and come, ok. Of course, more commonly we can also write this as pulse repetition rate, right is 1 by T R. So, this is a very important parameter that is going to dictate how fast you can send the next pulse. So, pulse repetition rate is going to be depend. So, if you fix pulse repetition rate, in some sense you are determining how deep you want to listen, ok.