Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer

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Week – 09

Lecture - 45

Laser Doppler Velocimetry – 4

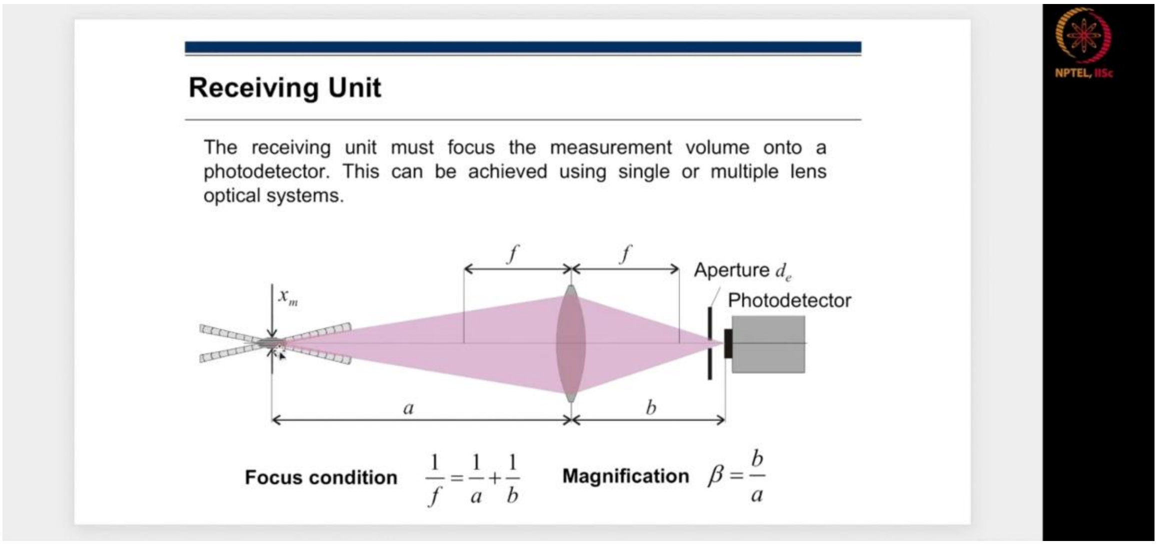
All right, so we have come to this portion of LDV. So this is what the receiving unit of the LDV looks like. Remember, we already did the transmission part. So what happens is that you have the measurement volume, and then you collect it using a lens assembly, and then you focus it, perhaps, on a multimode optical fiber. And then you can even pass it through interference filters if you want to separate out colors, etc. At the end, there is either a photomultiplier or a photodiode, which actually receives the signal.

This has a very high frequency response, so this is what your collection optics actually looks like. So the filter is mainly for splitting the colors and provisions for that. Using this kind of arrangement, technically, you can actually measure different velocity components as well. So that is possible with the LDV.

So this is the collection optics, or the receiving optics, essentially. So if you look at it in a more systematic way, this is the measurement volume, which has these fringes, and the two laser beams are actually intersecting there. And then you have the lens. Again, it's a thin lens. So basically, you collect it, and then you focus it on the photodetector, which can be a photodiode or a photomultiplier tube.

Now, sometimes you put an aperture in front of this photodetector. Now, the question is why do you want to put in an aperture? This can be a pinhole, or it can be a slit. And for the other lens formulas, the magnification is given, for example, by b/a. So this is all we have covered earlier.

$$\frac{1}{f} = \frac{1}{a} + \frac{1}{b}$$



This is a standard lens formula. But the aperture is interesting. This aperture can have a diameter or a slit width that is of the lens scale DE. So why is that required? So the aperture is often placed in front of the photodetector. So what it does is restrict the dimension of the measurement.

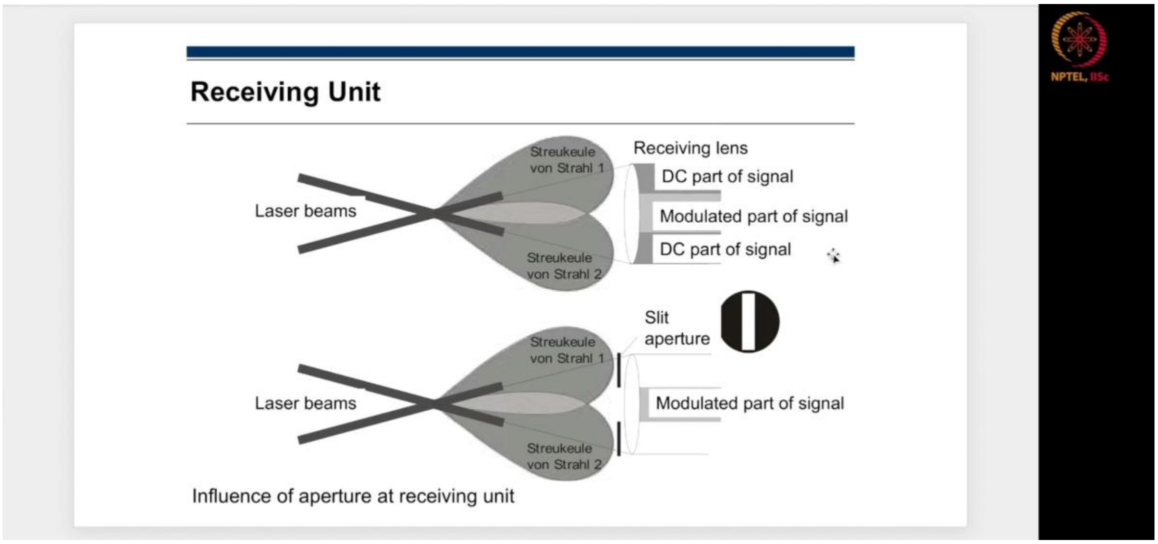
Volume from which the signals are generated, so as you know, our measurement volume—we talked about the measurement volume, we talked about the detection volume—and we also saw that, okay, the particles that were actually passing through the edges will have a lower amplitude, or rather a lower intensity. So what you can do is restrict. Using an off-focus aperture restricts the dimension of your measurement volume. As a result, you increase your spatial resolution quite well. Now, for measurements, for example, which are very close to the wall, or measurements where your measurement dimensions need to be of the order of micrometers, the LTV may be necessary because you may need to measure a point that is very close to a wall in a very turbulent flow.

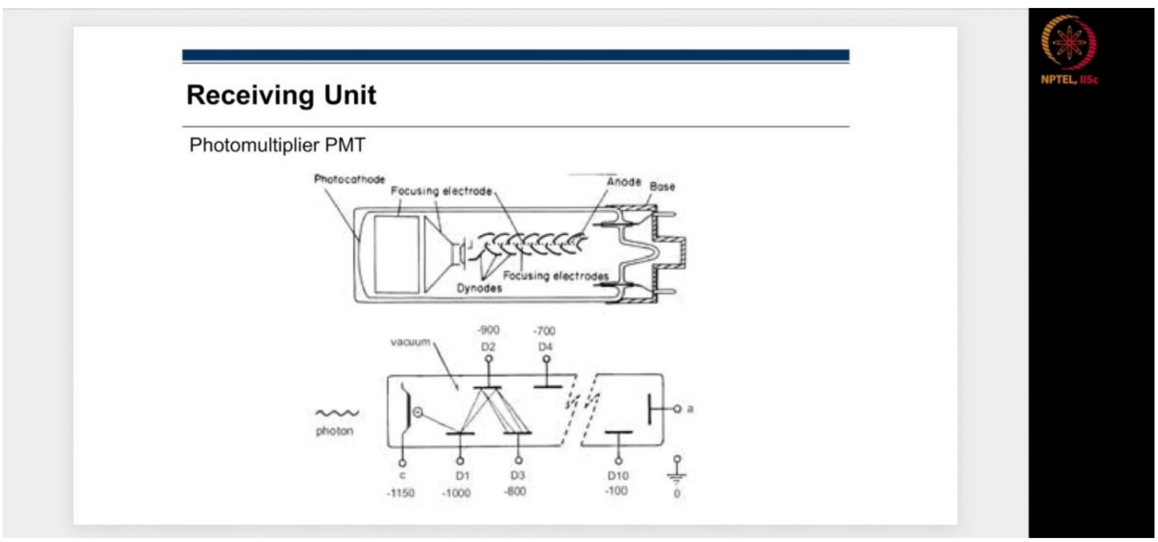
So the LDV will actually enable you to do that because you can restrict the measurement volume to a very small space by using the expander as well as this aperture. So, you can substantially increase the spatial resolution. When you place this, you know, this photodetector in a sight-scattered mode, this aperture significantly reduces the length of the measurement volume. So, for example, the measurement volume lengths from 20 to 50 micrometers are routinely achievable in this particular manner. Remember that we had more of an extended or a cigar-type measurement volume.

So it can reduce the length of that measurement volume to something around 20 microns all the way up to 50 microns. So this is critical because, you know, your normal PIV, though it is very good, still cannot achieve the same level of spatial resolution and temporal resolution that we can achieve with an LTV. But the unfortunate part of this is that the LTV is still a point measurement, or the measurement volume is rather small. But sometimes, you really want that. You need to know at a particular point what the kind of velocity, vorticity, and what kind of profile you are generating is.

So, the aperture can significantly reduce the length of this measurement volume, thereby increasing the spatial resolution. And it basically restricts what is the signal that you have generated and defines the detection volume in this particular fashion. So the receiving unit basically has lenses, which actually have the DC part of the signal and the modulated part of the signal, which we already talked about; the DC part is basically like the envelope, and the modulated part is the oscillation that sits on top of it. And this is the slit aperture, for example, that you have, which restricts the DC part quite a bit and allows the modulated part to enter. So if you look at the receiving unit's perspective, this is like, for example, a photo multiplier tube.

So what happens is that the photon comes and hits the microchannel plate, and this actually leads to an avalanche of multiple electrons, and that is what actually goes into the detector. So this can actually have a very high gain. Photomultiplier technology is also used in your image intensifiers. So used by the army initially. So this is what actually happens.

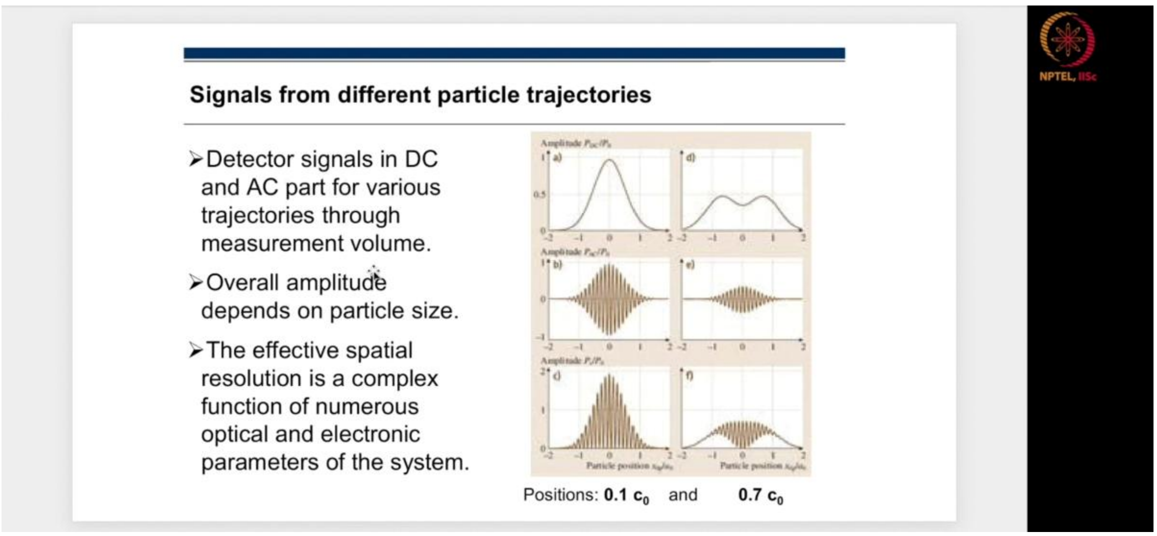




So you have a very small number of photons coming and hitting, but it can create an avalanche of electrons, which ultimately gets detected in your detection optics. So, the photomultiplier tube is one of the key elements. It's expensive, but it is also routinely used in many measurements. The technology is there. You know the technological aspects of it.

So, that is what actually works over here. So this is the same technology that is used in your intensified CCD camera as well. So let us look at the signals from different particle trajectories. So as you can see, this would be the typical signals. This will be the signal for a particle that is passing through the middle of the detection volume.

And this is the amplitude part, and this is the DC part of it. And if a particle is passing through one of the edges, remember that it looks like an ellipsoid, and this is a very extended kind of cigar-shaped measurement volume, so the particles that are going through the edge should have this kind of a thing. There is a little bit of a burst, and if you isolate this, this is the AC component, and this is the corresponding DC component. So the detector signals in the DC and AC parts for various trajectories through the measurement volume are what is shown over here. So the overall amplitude, of course, depends on the particle size.



The effective spatial resolution is therefore a complex function of the optical and electronic parameters of the system that we can see over here. So this is what the receiving optics actually see. Now, if you also look at it carefully, when we talk a little bit about the filtering portion, the left side is basically the background noises at the edge of the burst, which is reduced with a baseline clamp filter. The Doppler frequency is removed by a low-pass filter. So this is the result of a pedestal.

And the truth is that the Doppler signal passes through a band-pass filter. This is used for determining frequency. By rectification and low-pass filtering, the result is an envelope. A pedestal and an envelope can be used for particle detection. That is when a particle is in the detection volume.

Okay, so this is how the filtering operation actually happens in the case of the Doppler signals if you look at it carefully. You can see that we already talked a little bit about the filtering earlier as well. But the interesting part will be the signal detection or the signal-to-noise detection. So, look at it carefully.

This is the signal. This is the signal that you receive on your photodiode or PMT. If you take a power spectral density of this, what you are going to have is two peaks. One peak will be centered around zero, which basically gives the DC component. The other one will be the actual frequency, which is the Doppler burst frequency, centered around this, which is FD, that you can see over here. Now, if you take an autocorrelation of the signal with itself, it will also give you the same profile, which is essentially like this.

So, this is the time lag, and this is, like, you know, the time lag, and this is the autocorrelation function that we have plotted. The autocorrelation function of a sine wave is essentially a sine wave. OK, so this is what you get. Now, let us look at white noise. White noise, by nature, contains all frequencies.

So this is what a white noise spectrum typically looks like. By taking a power spectral density of the white noise, you will get all these frequencies present. So these are all the frequencies that you see, unlike the very sharp frequency that you have. Now, the white noise, if you take the autocorrelation function of that with itself, basically, what you get is a peak that is centered at t equal to zero. So this is the autocorrelation function of white noise on itself, basically.

So this will give rise to a peak at 0. In frequency space, if you look at it, all the frequencies are present. When you take the autocorrelation, it is centered around 0. Look at the autocorrelation function of a sine wave, which is the original signal.

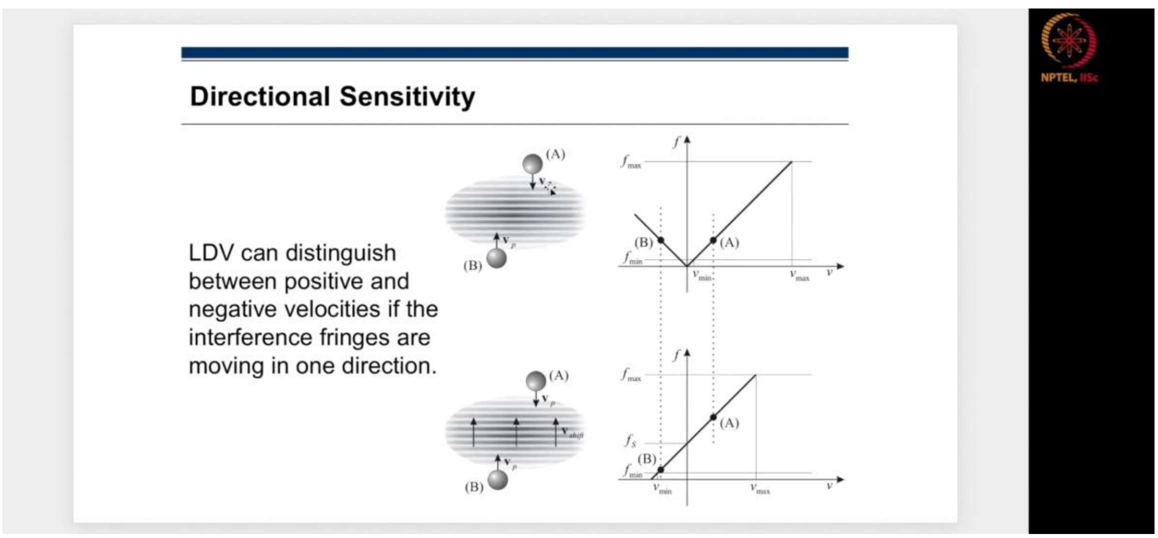
It looks like this. And the power spectral density will give you a sharp frequency, which is the Doppler frequency that you have. Now, if you add these two functions, this white noise is added to the signal because you can have sources of errors or sources of noise. It can be electrical noise. It can be the room's light.

It can be scattered light from dirt. It can be from optics that have gone a little dirty, for example. All of these are part of the white noise. And it has no structure, actually. All the frequencies are present. So when you add these two, you get a signal that is something like this.

So the noise is somewhat embedded in the signal. So now, if you take a power spectral density, you get this zero-valued frequency. Of course, that is the DC component. Then you still get the sharp peak. and you have all the frequencies now, which are present as small sidebands, which are spread all over the spectrum.

Now, if you take the autocorrelation, you will see this is this profile plus this profile, and it will give you a sharp peak, an extension, basically at zero. So this is the way that you actually analyze the signal. Now, if you look at the area under the curve, for example, here, like the area under the peak section, and then you take the area under the noise, and then if you divide one by the other, you can come to the conclusion that the area under the peak and the area under the noise, if you take those two things together, and take the ratio of the two, now you can have. You can establish your own threshold where you can say that you are only going to accept values where the signal-to-noise ratio is beyond a certain value. That means if this area and this area become very close to each other, or the signal is now embedded in the noise, or the signal amplitude is embedded in the noise, then we say that we discard those values.

So it actually provides that your measurement would be actually clean. So we preferably want a high signal-to-noise ratio. That is all that we want in this particular case. So that area is this, and this is the area under this curve. So if you divide one by the other, you should get a good signal-to-noise ratio.



So this is how the detection actually happens. Now the other part, we get a little bit of complexity that comes into the picture because the LDV, like the way we analyzed it here, does not have a directional sensitivity. That means if you look at the fringes, these are the fringes over here, and say a particle is moving in the downward direction versus a particle that is moving in the upward direction, right? Both they say that they have the same velocity V_p, but they have different directions. So if you look at this particular plot, this is v and this is with respect to the frequency. So say you have a velocity a, and for that particular velocity, you get a certain frequency. Okay, now if you have the negative velocity, so the velocity is in the negative direction, you get the same frequency.

So, just by looking at the frequency, you cannot tell which way the particle is actually going. So it cannot really distinguish in its current form which way the particle is actually going when you are looking at the stationary fringes. Because A and B are your variables, though in reality, the velocity vectors are opposing each other from a frequency perspective, because that is what you are using to measure the velocity. Because your frequency, remember, is linear with the velocity.

You don't have a bias, therefore. So you don't know which way the velocity vector is pointing. So to solve this particular problem, what you do is that if you can have moving fringes, if the fringes are moving with a velocity V_{shift}, say for example, they are moving upward with a velocity V_{shift}. Now, if you have a particle that is going with the fringes and a particle that is coming against the fringes, these will be different. So this will be very different. So when the particle moves, you can see that the fringes here are moving upward with a V_{shift} .

So basically, what we have done is add another frequency. It's a frequency at which the fringes are shifting. It is the frequency at which the fringes are shifted. As a result of that, what will happen is that your B will show a different frequency than your A.

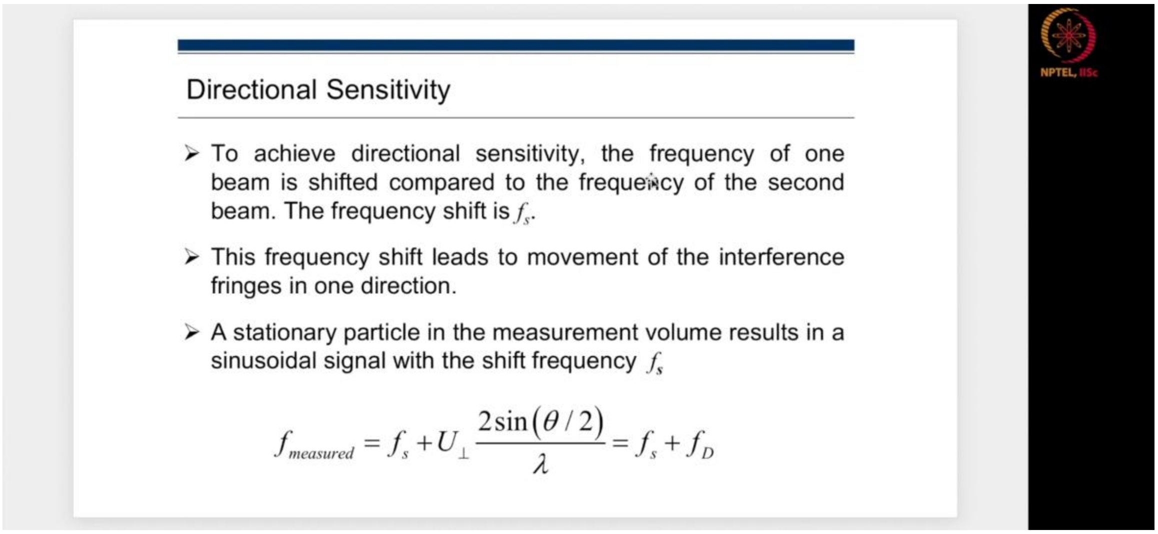
So A is moving, and the fringes are moving towards it. It will have a different frequency compared to point B, which is moving with the fringes. Therefore, it will have a frequency that is different. And f_s is basically the frequency of the shift of this fringe shift. In this way, though they have the same velocity, they have the same velocity but different directions; we can actually now find out what the directionality will be. So the directional sensitivity can now be measured using this kind of measurement.

So how do we achieve this directional sensitivity? Now, to achieve the directional sensitivity, what happens is that the frequency of one beam is shifted compared to the frequency of the second beam. So this frequency shift between the two beams, let's call it FS. That is the frequency shift. This frequency shift leads to the movement of the interference fringes in a particular direction.

And that is what the V_{shift} is all about. Now, a stationary particle in the measurement volume results in a sinusoidal signal with a shift frequency f_s . Now, if the particle is stationary, what you measure will be the shift in frequency. Now, if you add a velocity to the particle, you add this. Remember, previously it was only the second term.

Now you have added an "f_s " on top of it. So what it essentially measured is f_s, which is the frequency shift, plus what the velocity is, which is the Doppler shift of the frequency.

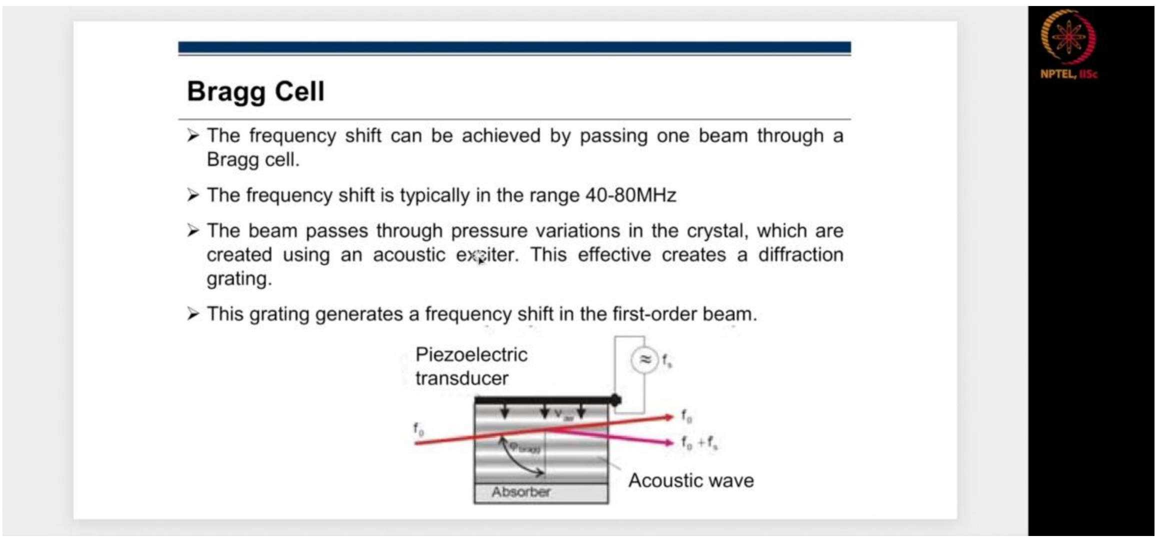
Now this can be negative depending on whether you actually go down in velocity. That means the velocity is in the other direction. Okay, so it's a very simple thing. You add a frequency shift; basically, you are adding a bias in which now the velocity, if it is moving with the fringe, will be different from the frequency that you measure when it is against the fringe.



Okay, so it is basically this shift frequency plus the Doppler burst frequency. This we already know is what it is. We are just adding a shift frequency to this by changing the frequency of one of the beams compared to the other, and this automatically leads to a velocity of the fringe. So if the particle is stationary, say for example, the particle is sitting here and not doing anything because the fringes are moving over the particles now, this will give rise to an fs that your photomultiplier tube or your detection optics will measure. So you understand, if the particle is sitting here and the fringes are moving over it with a V_{shift}, that V_{shift} ultimately corresponds to a frequency of f_s.

Now, if the particle is now moving along with it, basically, it's like a relative velocity you are going to measure; depending on which way the particle is going, okay, with the fringe or against the fringe, you are going to have the Doppler burst. So by introducing the shift, you can actually frequency shift; you can detect which way the particle is moving. How is this done? This is done using something like a Bragg cell. So what the Bragg cell does is that you have, you know, a cavity or an exciter, which can have water or it can also be glass. So there is a piezoelectric transducer on one side, and then it's an absorber on the other side.

So what it does is create a stationary pressure wave. So these are the stationary pressure waves, the nodes, and the antinodes. So when the laser beam actually passes through it, through the pressure variations in the crystal, this particular variation in pressure is actually what creates what we call a diffraction grating. So when the beam passes through the pressure variations, this effect creates a diffraction grating, which now creates a frequency shift in the first-order beam; this is the first-order beam, and this is the zeroth-order beam, as you can see the red and the pink parts. So what we do is, in this cell, which can be glass or water, by using a very tightly controlled piezoelectric transducer and absorber, you create a certain pressure.



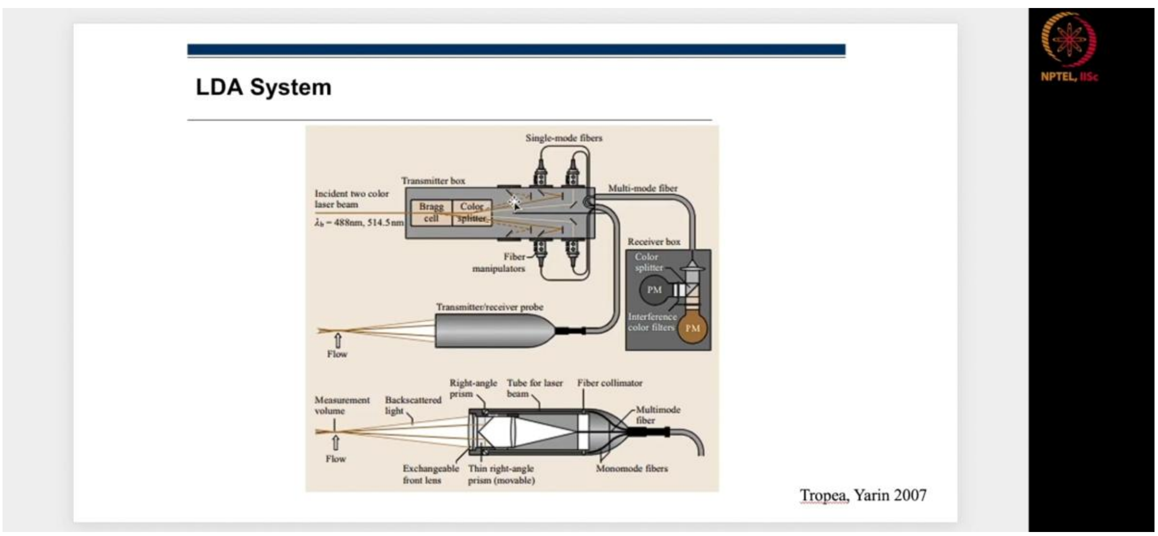
stationary pressure wave pattern. And this therefore creates the diffraction grating. You can also use a mechanical diffraction grating; that is also possible. So the beam that comes out has a frequency shift in the first-order beam, while the zeroth-order beam still preserves the same frequency. Okay, so this is the Bragg cell. So this is how you can create a shift in the frequency of one of the lasers.

So, how this is done: if you look at it carefully over here, this is the laser, this is the collimating optics, and this is the Bragg cell. Now what you do is that after it passes through the Bragg cell, there is a zeroth-order beam and a first-order beam. So then do the lensing, focus it at a tight measurement volume, and then collect it. And what you collect is going to be the Doppler burst plus the shift frequency.

So this is one way to do this. You can also separate the laser beams into two parts, use two Braxels, introduce a little bit of a change in frequency in both, and focus it once again over here. So what this photodetector now measures is the Doppler burst plus the difference in frequency between the two. So here only one beam is actually frequency shifted; here both beams are. As a result of that, the difference is what actually matters, and that is what you should be concerned with.

So this is how these things are actually done. Now you can utilize these systems; you can have two color beams. So, for example, there's a Bragg cell, and then there is a color splitter. So you have green, and you can have blue, and you can have green width. The frequency shift and green without frequency shift are done the same way for the blue; in this way, you can separate the two components of the velocity, and that can be done, and it is collected in the backscatter mode so that you don't have any alignment issues at all. You can have situations where there are two components, and then you can have a third component as well.

So this is a combination of two things. So you have a 2D LDA, and then you add another 1D LDA on top of it. All needs to be focused on that small measurement volume. So, for example, it is green, blue, and magenta—three colors. As a result, this is a pretty onerous task.

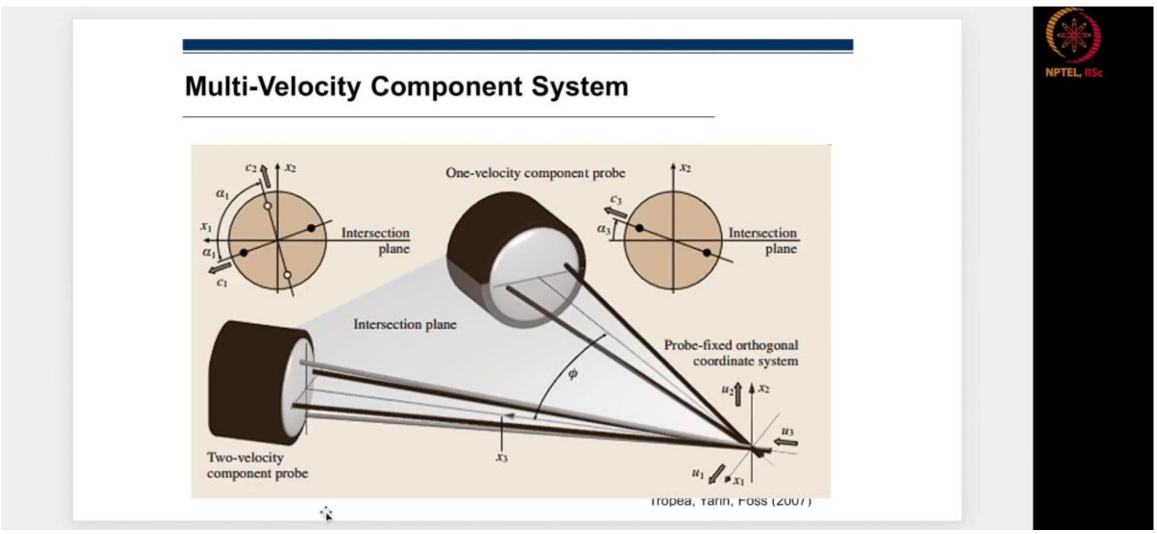


I mean, focusing all of them on a very tight spot size is not trivial. So this leads to many alignment issues. So, 3D LDV is not trivial, I mean. So even 2D is not very trivial. And lastly, you have the multi-velocity component.

So these are the different ways. This is an example of measuring something in the showroom. And so you can do all of this. So this is actually a three-component. You can see there are two; you know, this has got two colors.

This has a single color. All of them are focused on a particular measurement window. So this is how it happens. This has got two velocity probes.

This is a single-velocity probe. All of them kind of merge here. And then, using the frequency shifts and all other factors, you can determine the velocity in three directions. And this measurement volume can be very tight, as we saw: 10 microns, 20 microns. It can be very tight by using a combination of apertures, expanders, and other similar tools. So the LDV summary is basically a non-intrusive point measurement technique for one, two, or three components of velocity, exhibiting very high temporal and spatial resolution as well. So the advantages are that this is non-intrusive, there is no calibration, there is no drift, and its frequency is directly related to the velocity.



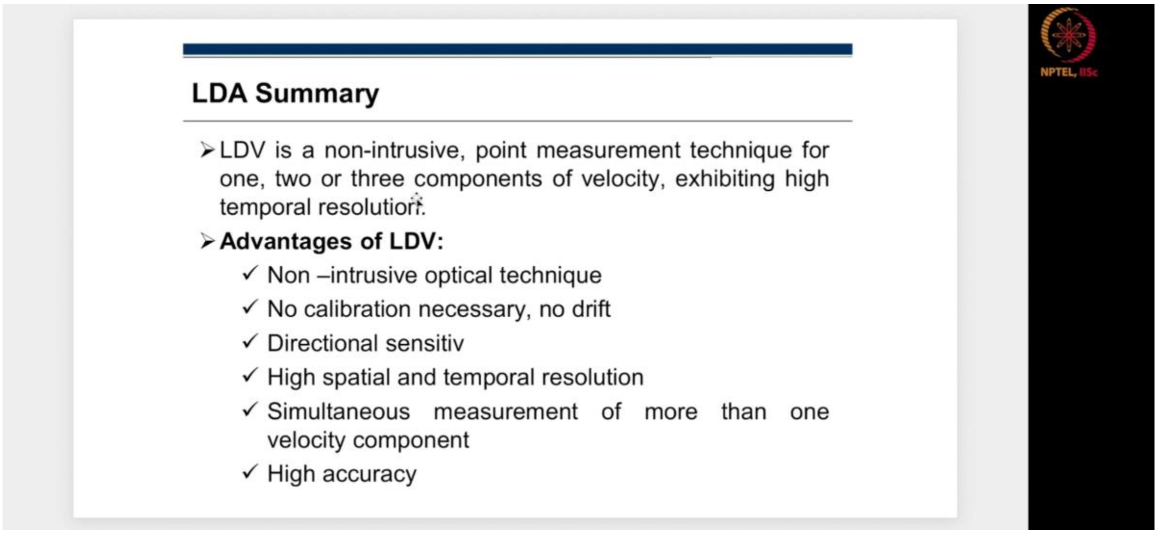
It can have directional sensitivity by using the frequency shift that we discussed. It can have a high spatial and temporal resolution. You can simultaneously measure more than one velocity component. It is highly accurate. That makes it a very good candidate for turbulent flows, as well.

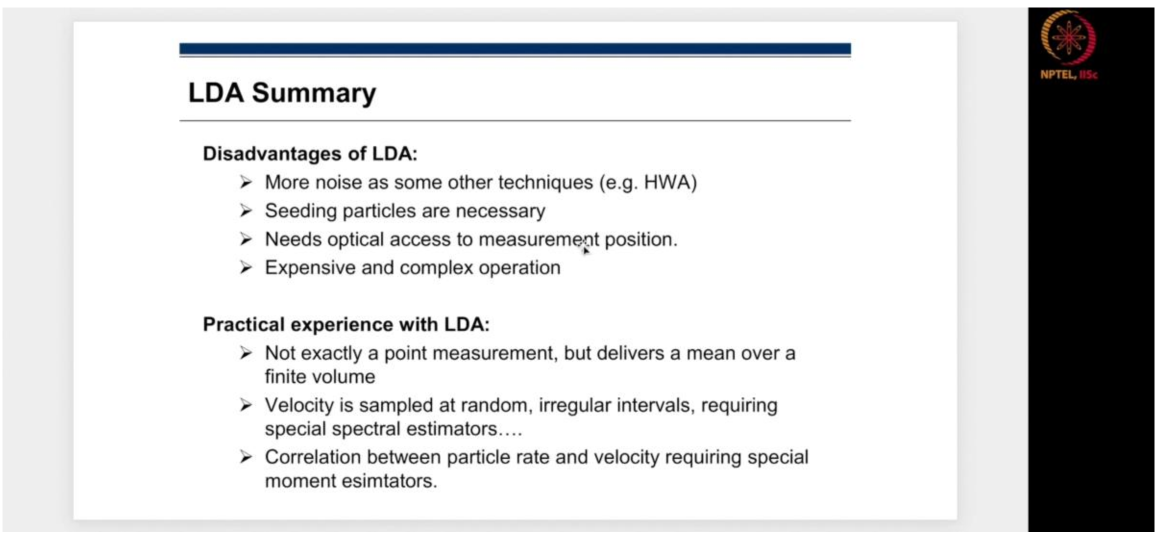
The disadvantage is that it can create more noise. Hot wire anemometry, which we already covered, is compared to hot wire anemometry. You need seeding particles because you need particles that will actually scatter the light. And these seeding particles need to follow the flow; they need to be large enough as well as small enough—large enough to scatter enough light, small enough to follow the flow. It also needs optical access, which means you need to have the laser light pass through. Unlike PIV, which requires a lot of optical access, here the optical access can be restricted, but it requires that optical access, and it is expensive equipment to buy.

So it is not exactly a point measurement, but it delivers it over a finite volume. The volume is, however, very small. The velocity is sampled at random, irregular intervals. So, we also said in our hot wire anemometry lecture that this is not a continuous analog signal. And the correlation between the particle rate and the velocity requires special moment estimators.

So, these are some of the practical experiences of using LDA. So, it's not a very easy

technique per se to be useful. Hot wire anemometry showed that it is more like an analog signal, but it has its own problems because it is also intrusive in nature. So this is literature. Most of the notes are taken for Professor Tropia's lecture and also from his notes, which he has been kind enough to let me use.





So this is the Handbook of Experimental Fluid Dynamics. This is a very good book. Edited by Tropia and Yarin. Then this paper also discusses laser Doppler and phase Doppler techniques. This is also a very good one. And then you can also look at Durst, Melling, and Whitelaw's The Principles and Practice of Laser Doppler Anemometry.

This is also a very good book. So these are some of the literature. We have skipped a little bit of the math, but as you can understand, most of it should now be understandable. Of course, you need to do it to understand, for example, the practical side of it and the alignment side of it. That requires you to work in a lab setting. But this is basically the theoretical concept of laser Doppler velocimetry. Thank you.