Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer
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Week – 10
Lecture - 46
Phase Doppler Particle Analyzer – 1

All right, uh, today we are going to take our first peek into what is called the Phase Doppler Particle Analyzer, which is uh, PDPA. Uh, these lectures are also taken from uh, Professor Cameron Tropia's book as well as his lecture here at IISc. Uh, he is one of the pioneers in the PDPA technique, as we all might know. So, uh, we have done LDV already; we have done all these lectures on light scattering and stuff like that, so the PDPA will be a little bit, you know. What we call easier to comprehend with that particular background. So, without wasting time, let us go and see.

So again, we are just going to spend a few minutes reviewing light scattering from spherical particles and then discuss the principles of the phase Doppler measurement technique and how the phase Doppler technique is realized: standard system, planar system, or dual mode system. And we are also going to take a sneak peek at interferometric particle imaging as well. So the measurement techniques for droplets, as we know, are a fundamental piece in most applications because they are multi-phase, and multi-phase usually involves droplets in one way or another. So there are direct measurement techniques that measure size, velocity, and shape, such as PDPA, PIV, shadowgraphy, and clear point separation.

We will see what it means. There is also intensity and density ratio, so there are extinction-based measurements, like real extinction measurements. There is also the lift ratio, two-band, three-band lift. Lift is laser-induced fluorescence, stuff like that. There are interferometric techniques, like laser Doppler, phase Doppler, and eyelids, which is basically the.

Mesurement Techniques for Droplets

Measurement Principle	Measured Quantity	Measurement Techniques
Direct Imaging	size velocity shape	PIV/PTV Shadowgraphy Glare-Point Separation
Intensity, Intensity Ratio	size temperature Species	Extinction/Absorption Modulation Depth Mie/LIF Ratio Two-Band/Three-Band LIF
Interferometry	size velocity refractive index temperature	Laser Doppler Phase Doppler ILIDS/IPI Fraunhofer Diffraction Rainbow Refractometry Holography
Time Shift	size velocity (refractive index)	Time-of-Flight Pulse Displacement Time-Shift Technique
Pulse Delay	size velocity	Femtosecond Laser Methods
Raman Scattering	temperature species concentration	Raman Spectroscopy

Adapted from C. Tropea. Optical particle characterization in flows. *Annual Review of Fluid Mechanics, 43(1):399–426, Jan. 2011.*

.. The content of this particular lecture includes the measured quantities of size, velocity, and refractive index. There are time shift techniques available that also measure size and velocity, as well as pulse delays. Additionally, Raman scattering is used for Raman spectroscopy due to its specificity. Raman is a highly utilitarian method, but it has very low   sensitivity.   signal-to-noise   ratio.

 So it is also used for temperature and species concentration measurement. So there are a lot of diagnostic tools available in the community where you can measure different things like temperature, size, velocity, and so on. So this you have already seen in our lectures that when there is an incident plane wave which interacts with a particle of homogeneous material, it basically scatters in all possible directions, and the exact solutions of these problems are given by the Lorenz mean theory. This was also what we said that, uh, you know, scattering by a spherical particle is described by this theory, and we basically um In order to quantify scattering, we advocate a parameter called the me parameter, which is basically nothing but the non-dimensional diameter, given as $\pi d_p/\lambda$, where d_p is the size of the particle and λ is basically the wavelength. And this is a function of the relative refractive index.

So the scattering is a characteristic we saw in three ranges. When the particle size is really small in this particular zone, we get what we call Rayleigh scattering. In the middle zone, which is from about 0.2 to about 10, we get what we call Mie scattering. Remember, this is for a lambda of 488 nanometers.

And in the geometric optics range, when the particles are very large, you get a very large intensity. So relay scattering is by far the weakest phenomenon. And it should also be mentioned that it depends on what scattering angle you are actually monitoring or quantifying the signal. All right. So this is the "Mie" parameter.

This is the particle's diameter. This is the intensity. All right. So this is the basic premise that we already did. Then we also did something called the.

Interaction points, for example, when there is illumination, you get a shadow, and then you get the refracted background light, which is given as a bright spot over here. This is also done, and then if you shine a laser, you get further spots. This is with background and laser illumination. And if you recall that this was the first glare point, glare point, first-order refraction. And this is the glare point for reflection.
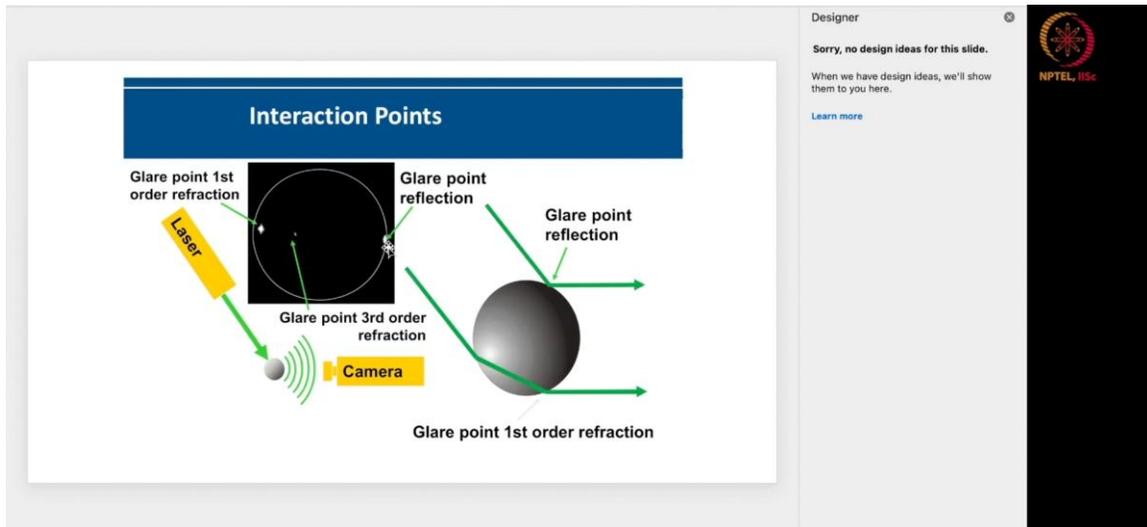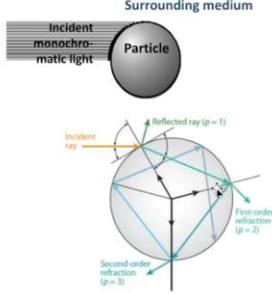
So this is how it happens. And this is how the first-order refraction actually takes place. So you are just shining a laser. This outline is just for, you know, visualization purposes; that outline does not exist, you just see the glare points, okay? When you shine a laser, a monochromatic radiation, now when you actually do an illumination like this, and you know there is a certain angle at which you are receiving a scattered signal, one can see that this is the first incident point of first-order refraction; this is a clear point. And this is the incident and the glare point of the reflection.

This is also something that we have covered. So if you now have a series of monochromatic incident lights that are incident on a particle, this is the surrounding medium. So geometric optics describes the light scattering from small particles using the laws of reflection and refraction. The assumptions are made that the particle is spherical and that the light is monochromatic. So then we found out that Snell's law and Fresnel's equations can be used to compute the reflection and transmission angles.

You can see if this is an incident light; part of it gets reflected, and part of it enters. The first thing that gets out is the first order refraction. Part actually goes out and then comes out on the other side, which is second-order refraction. And this continues for a while.

All right. And this is the signal that you receive. And this is diffraction and reflection. Remember, this is Brewster's angle. And this is the total signal that, you know, the phase Doppler anemometer will actually receive. This is what we are going to talk about later.

Okay. This is first-order refraction. The first order refraction, as you can see, is the reflection curve. This is the first-order refraction. So you can see that this is the region where phase Doppler usually works. We will come to that; that's why it works in that particular region.

Now, if you look at it from a geometric optics point of view, there is an incident wave, and then there is reflection, diffraction, first-order refraction, second-order refraction,

third-order refraction, all these things, and other scattering modes. And in certain modes, they actually interact with each other, giving rise to interference fringes. And that is exactly what happens; you know this is light scattering by small particles, so there is, you know, parallel polarization. Okay, as you can see over here, this is for parallel polarization. So there is, you can see reflection; you can see first-order refraction, third-order refraction, and so forth.
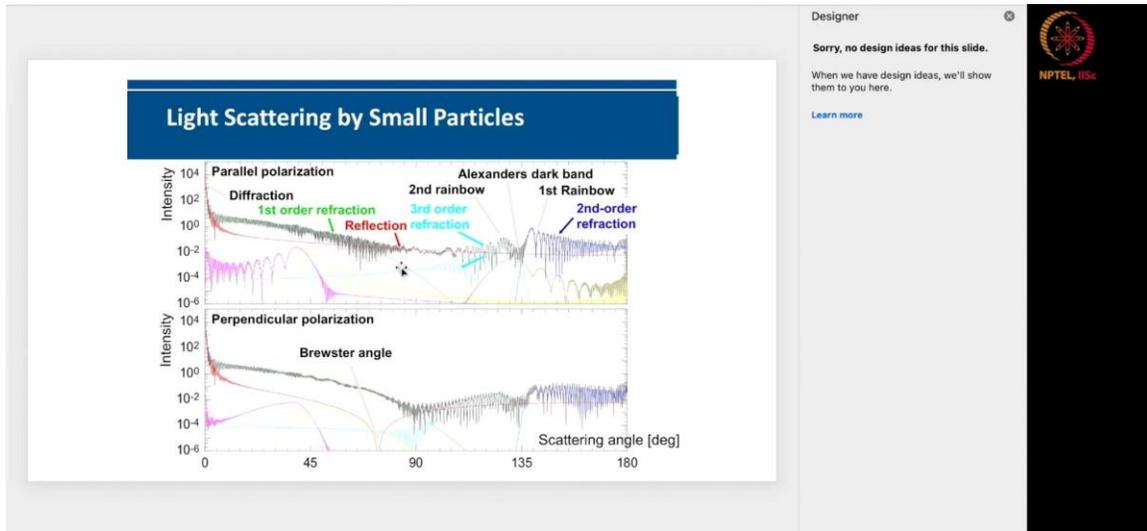
And this is for the perpendicular polarization. Recall what we did for perpendicular polarization. Is the s polarization essentially so this is actually the Brewster's angle; this is the scattering angle. It is just opened up, so the entire polar coordinate has been opened up, and at different scattering angles, you will get different dominance of the different modes. For example, at this particular angle, you will get first-order refraction mostly and a lot of reflection as well, but if you go to other modes, you will see the dominance of some other things as well.

Okay, so this is how these things actually work. So this is the dependence on the relative refractive index. For example, if it is water and air, and the droplet is, say, water in an air medium, it is fairly easy. But these curves actually depend on the relative refractive index as well.

This also we told. And this is for very small particles, like relay scattering. This is the kind of intensity on a logarithmic scale that you would get. And for large particles, and even for medium-sized particles, you will get this. So forward scattering, we were told, is much larger than backward scattering. So this is how all this is known to you.

So now we go to the principles of the phase Doppler measurement technique, now that we have a little bit of a prelude to what we did earlier. So let's look at this. So this is what phase Doppler actually looks like. It's a little complicated, as you can see. So, you can see that the initial thing is the same as the laser Doppler.

So you have a laser light, a collimator, and then a beam splitter. You split the beam into two, and they are at an inclusive angle of theta. They are made to converge at a particular point, which is exactly what we did for the LDV. And then you have two detector probes over here, which are basically off-plane. So these two detectors are positioned out of the plane of the incident beams.

At an angle that is usually called the off-axis angle of Φ_r. So this is Φ_1, and that is Φ_2, so this is like Φ . And the detectors are also placed symmetrically out of the y-z plane, if you look at the y-z plane. So it is placed symmetrically out of the y-z plane by an angle of ψ, which is ψ_1 and ψ_2. Okay, so this is the arrangement that we are talking about.

So, we'll see more about it a little later. But this is the basic arrangement: you have a laser that basically does the same thing; this is exactly what your LDV actually does. But now you have two detectors that are basically placed off axis. Okay, out of the plane, essentially.

Okay. To know about it in more detail, you see this is what happens. So these are the two beams that have an included angle. They are made to converge at that point, which is the measurement location. These are the droplets of the particles that are passing through it, either upward or downward. Now, these two detectors, which are U_1 and U_2, are placed

at   the   same   scattering   angle,   but   they   are   placed   off-axis.

They are placed off-axis at a scattering angle. And they are also at a certain elevation angle, which is shining. So they are at an elevation. So they are moved from the axis at a particular angle, whatever that angle is of your choice, which is this phi that you see over here. And then they are also elevated above the plane.

So that is the thing you should remember. And then theta is, of course, the beam intersection angle, and m is the relative refractive index. So if this is the droplet, this is like   the   meridional   line   connecting   the   two   poles,   essentially.

So if you... What are you going to monitor for small droplets? If you just look at the droplet, if you zoom in, you can see that part of the light actually goes through the droplet in a certain way and part goes in a different path length. So the direction gives rise to this interference fringe when it reaches the detector. And if you have a larger droplet, this is well indicated, you know. So, you know, the light that is entering here gets first, this is first-order   refraction.

And this is also the first-order refraction. Both of them pass through the droplet, but essentially, they have a path difference between them. So when the path difference is small, the fringes are basically a little farther apart. When the droplet is large, the fringes are   closer.   They   are   actually   closer.

So this is what you see in this particular case. So this is a small particle. So if you just look now from the top view, you will see that this is what the detectors actually see for a

small particle and for a large particle. So this is the superimposed wave from the two glare points. Okay, so because these are the two glare points that you can see over here, right, from the two beams, now if you know the distance between the two glare points, that is also related to the diameter of the droplet, because as you know, the smaller droplets actually have very low spacing. And between the fringes, larger droplets appear higher, but this gets reflected in the spacing of the fringes that you are supposed to get at the detector site.

So there is what we call a phase shift, denoted as delta phi, which is the phase shift measured by these two detectors. So it is a phase shift between these two detectors. What does it do? Let's look at it carefully. So the phase shift, if you are observing the reflection mode only, indicates that if you look at the two signals, you will see that the red is from one detector, while the black or blue is from the lower detector.

You can see that their frequencies somewhat match. They are at the same scattering angles. The frequencies match, but their phases are off by a little bit just because of the path difference. OK, just off by a little. OK, you can see that they are off just a little bit across the board.

So, this is the time. This is the signal's amplitude. So remember one thing that you know. Just to clarify, one can technically measure the fringe spacing and infer what the diameter of the particles will be, but the point of concern is that the fringes are moving at megahertz; as a result, camera monitoring and imaging the fringes, and making sense of it, or basically finding the diameter at that high speed, is challenging. which is of the order of megahertz, is not possible. So, because the fringes are moving.

Phase Doppler Measurement Principle

Remember, these fringes are actually moving. And because these fringes are actually moving at that megahertz with the particle, measuring the glare points, or if you want to measure the glare points or the distance between the two fringes, is virtually impossible. So we do the next best thing. We put two detectors and measure; because they are at the same scattering angle, we measure the phase difference between these two detectors. The phase difference that is measured between these two detectors is a much easier proposition than measuring the fringe spacing, which is moving at a very high frequency. To avoid that, you use two detectors and measure the phase difference between the two.

But technically, as we can see by measuring the wear points as well, you can measure what the droplet diameter will be. That is possible. But here, by watching the fringes, you can also find out what the droplet diameter will be. Technically possible, but practically, it's a little bit onerous. So what happens is that if you now do a little bit of math, you will find that when you are talking about the phase difference between detector one and detector two, this is the relative phase difference.

Okay. So because the lights are coming, it is giving rise to these two beams that give rise to a fringe here and a fringe there. So, these are the two Doppler bursts that you see. And so there is an enveloping function, and then there is this oscillating function. So what happens is that you measure, you see the two profiles; the frequencies are the same.

It is just that there is a phase difference between these two. Now that phase difference, if you look at it, is directly linear to the particle diameter, which is d_p, and then there is a long term which is a function of, say, cos psi, which we know because this is how we have placed the detector. We know the laser beam diameter, half the angle, and we also know, you know. cos φ. Φ is how far away. This is basically the scattering angle at which we are monitoring it.

If you are dealing with reflection, you can relate the phase difference that you see between these two signals to the droplet diameter or the particle diameter, so to say. Okay, because all these parameters are known, you don't even need any calibration. If you do first-order refraction, you get a very similar result; it's also linearly proportional to dp, but then you get the relative refractive index. And in this case, the glare points lie on the meridional circumference of the droplet, which is shown over here.

This is the line. It lies on the meridional circumference, the two glare points. And again, you see that whatever is within these square root terms is a function of Ψ, Φ, and Θ divided by 2. All of these parameters are actually known. So, the relative refractive index is known. You also know the beam intersection angle, the elevation angle, the scattering angle, and the phase shift.

This is what you are measuring. And these are all given. This is what you actually know about all these parameters when you are assembling your setup or your tool. So the linear relationship exists between the phase difference of the signals from the two detectors and the particle diameter. As a result, you do not need any calibration per se. So calibration is not needed at all. Now, you see that when you are getting these kinds of, we will come to this in a second, because there are certain things that you need to know.

So just a reminder that you have the two Bragg cells, which introduce the frequency shift as well. So in this way, you know the frequency, which gives you a measure of velocity. And you know the droplet diameter. Okay, so both of these things are actually known. Now, here you have to look into one thing over here because you have derived it for first-order refraction or reflection.

So, you have to monitor it at an angle where the majority of the contribution comes from that particular mode. You cannot be in a region where all the modes contribute because, in that case, this relationship.

.. Will not remain exactly like this. So the math is even more tedious, and then you are going to have a little bit more terms and more complications to evaluate. So, in other words, the best way to avoid this is to have a predetermined scattering angle for a particular value; this is, for example, water in air. You can do it in a particular zone in which the specific mode is dominant. For example, if you do it here, these are the zones that are marked over here. If you do your measurement here, for example, you will find that the contributions from the reflection are like two orders of magnitude.
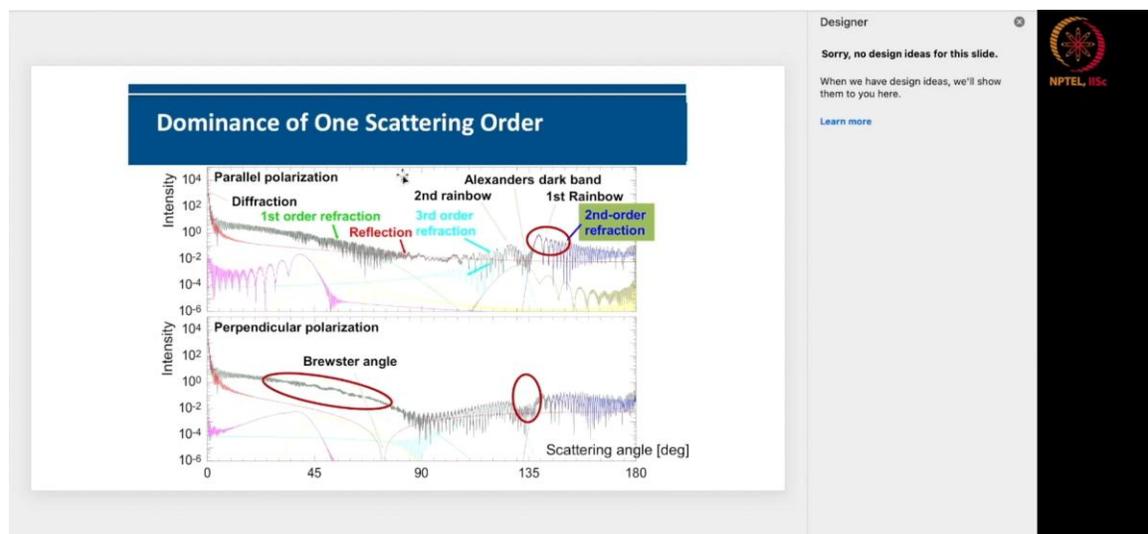
And the others are even lower because this is on a logarithmic scale, so here most of his contribution probably comes; this is for perpendicular polarization. Most of the contribution perhaps comes primarily from, you know, a particular mode. Similarly, when you do parallel polarization, for example, you see that this is first-order refraction. If you monitor somewhere here, you are at least 10 times higher than in reflection mode, and you should be good.

Remember, you also need to monitor it more closely within the 90 degrees. Because, as you know, forward scattering is more dominant than backward scattering, you always want to be here in these zones, okay? Mostly in these zones, so that you can actually take measurements and infer. You have to see where the next higher mode is, kind of off by 10 or off by 100. Accordingly, you choose your mode, and this is given for a particular m and a particular relative refractive index; it will vary if you change the refractive index. So the choice. When you try to set up your laser beams to enter a particular measurement volume, the angle from which you measure it on the other side matters a lot; whether it is head-on or at an angle is determined by these scattering orders and their dominance.

Of the scattering orders, you have to choose one of these modes that is well separated so that you can use one such relationship. That is the whole point, and remember this is the meridional plane or meridional circumference that we are actually dealing with here. All right, so this can be further translated into these kinds of maps, for perpendicular polarization, for example, as you can see. This is the angle of total reflection, the rainbow angle, and the critical angle, so you can see the different modes where the dominant or perpendicular polarization occurs.

In one case, this is dominant; this is two, and this is like one. And similarly, if you go for parallel polarizations for different scattering angles, you can see the different zones at which there is a dominant scattering order greater than 90%. So one order is about 90% more than the other order. So the linear relationship therefore assumes that one scattering order is dominant. This can be assured by a proper choice of the scattering angle depending on the relative refractive index. The figures, the contour lines of 92%, 94%, 96%, and 98% actually give you the dominance of one scattering order for particles in the range of 64 to 1290, which is 10 microns to 200 microns for water, which has an M of 1.

Selection of Detection Angle

The linear relationship assumes that one scattering order is dominant. This can be assured by proper choice of the scattering angle, depending on the relative refractive index. The figures indicate contour lines of 92%, 94%, 96% and 98% dominance of one scattering order for particles in the range x_M=64-1290 (10μm – 200μm for water m=1.33).

33. So this is just a selection matrix, a contour, or a regime map where you can park your measurement and make sense of what is going to be the case. All right, so the selection of your detection angle is therefore very important for you to apply this kind of relationship over there. All right. So the idea now is, how do you realize this phase Doppler technique? Because there can be a standard system, there can be a planar system, so there can be a dual mode system.

So in the next class, what we are going to do is look at that. But in this class, what we did was a review of the scattering of light from spherical particles. And we looked at the principles of the phase Doppler measurement technique. And how the phase difference is important because you cannot really measure the fringes that are actually moving or the difference in fringes that arises because of the particle, which is almost impossible, just because they are moving so fast. So you put two detectors where you measure the phase difference, and the phase difference is now linked to the droplet diameter, depending on the scattering angle, the elevation angle that you have chosen, and the relative refractive index of the medium. For reflection mode, the relative refractive index obviously does not enter into the picture.

It only enters into the picture when you are actually dealing with, you know, first-order refraction, but whatever it is, you have to use, you have to go to this graph and basically choose where one mode is dominant over the other, or you use something like this, which people may have done already for a particular fluid and for particular, you know, mean scattering parameters. Okay, uh, so you choose according to that. And then you know you should accordingly park your measurement. See, this is given for a fairly large size range, which is also important because in your measurement you can have polydispersed

droplets or particles that have a size range dependence, so you really need to choose your, you know, your.

your scattering order, so that it caters to a wide range of particles. So this is something that you know a priori, or maybe your theoretical calculations have given you the basis that this will be the dominant size range that we are actually looking at. There is no calibration requirement because of the linear dependence and because all the other parameters do not. The setup looks strikingly similar to an LDV. Okay, except now that you have two off-axis detectors at elevations, you can monitor the phase difference due to these particles, and then you measure the phase differences.

Basically, I'm looking at curves like this. This is what you look at. The frequency is already related to velocity. Shift now; that is the diameter. Thank you.