Spray Theory and Applications
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Lecture – 14
Spray measurements techniques

Welcome back, towards the end of last class we had completed our discussion of some mechanical measurement techniques that are applicable to measuring external spray characteristics. We will spend some time today talking about non-intrusive measurement techniques, to measure external spray characteristics both macroscopic and microscopic.

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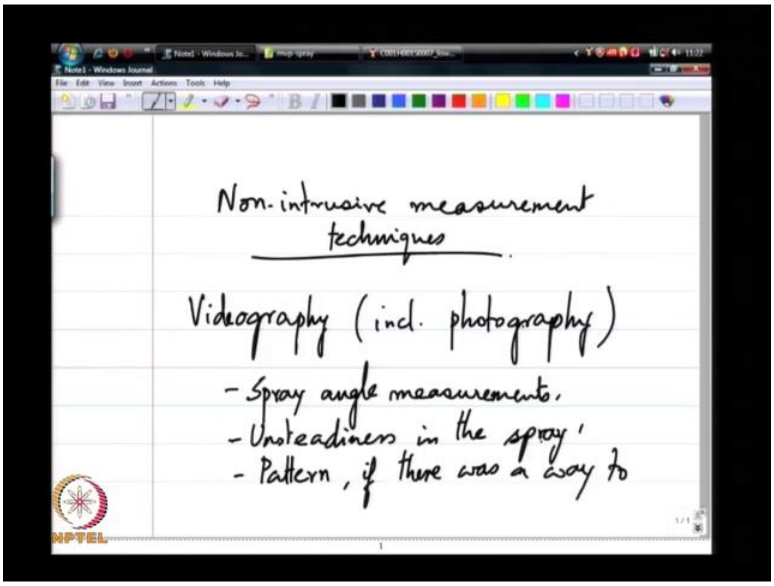

So, we will learn a little bit about Non-intrusive measurement techniques. So, will take the simple example of a Videography first, will see what a Videography which includes photography, what does it tell us and what does it not tell us.

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So we goanna start by playing very short video, as we can see this is the classic perfume spray we can pause the video here, in the classic perfume spray that tells us a little bit about the nature of the spray coming out of a standard perfume bottle, you can see that there are drops for downstream you can actually see the drops, but close to the spray nozzle itself you really do not see individual drops, but again close to the spray nozzle, you can understand the idea of a spray angle. So, macroscopic measurements such as spray angle and may be even spray pattern can be understood from a simple Video graph like this or a photograph, for even an individual photograph I will play this for a shot while.

Not only that as you can see, right now there is this is the case of a study spray in other words I had the perfume plunger depressed and that caused a study squared a perfume coming outer the nozzle at least seemingly study to my naked eye as I was spraying, but this video is a high speed video taken at about 3600 frames per second. So, at that resolution at that time resolution, you can see that there are structures as you can look at this little white patch, I am going show you can see that the white patch diffuses for the downstream, in there is another white patch that founds. So, it is not like continues spray it looks like there is some lens of unsteadiness. And other example is right here you can see that there is a little inverted v like structure, with the tip of the v pointing away from the nozzle, these are the classically so called inverted chevron structures that you will see in most spray. So, we will come back to look at the origin of one of this structures later on, but the point to note here is that in a simple video, we are able to make some sense of lot of these parameters. Now what other information can I get, let us talk about spray pattern for a movement, now this sprays presumably this axis symmetric.

So, what I am seeing is just the peripheral outside of the spray. So, if I have an axis symmetric spray, I am going to see in a video or a photograph, I am only going to see the outside, I am not really going to be able to see much of the inside part of the spray. So, if I want to see the inside part of the spray, if I want to sought of take a cross sectional view of the spray, which is what an in line patternator does.

So, if I want to take or if I want to take cross sectional if this is my nozzle back here and if this is a spray, if I want to take a cross sectional view in this sense and look at uniformity just like a sector patternator would do, I still need to figure out a where it make a cross section. And that is where this kind of illumination where we know essentially this is like asset of lamps surrounding this spray that were used to illuminate this particular spray, this is not particularly useful if you are do that. So, let us make some notes on what works and what does not work. So, one could make spray angle measurements, one could look at unsteadiness in the spray and you could also look at pattern if there was away to take a cross sectional view.

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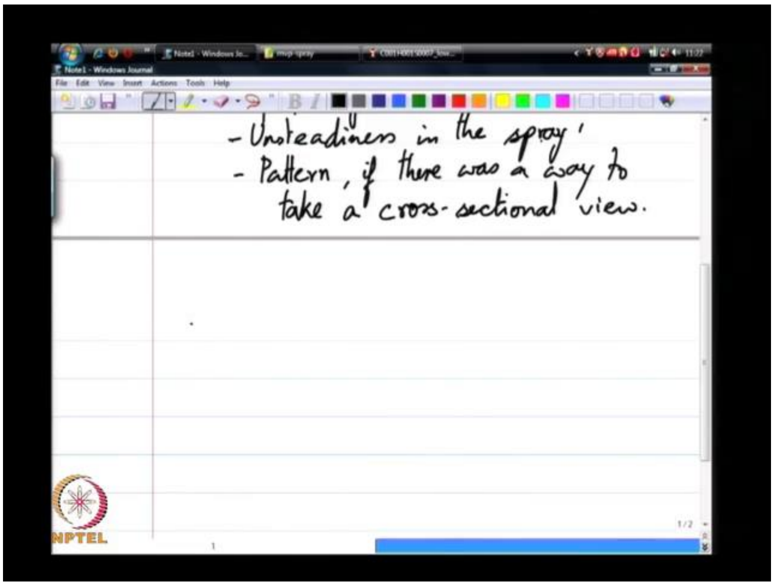

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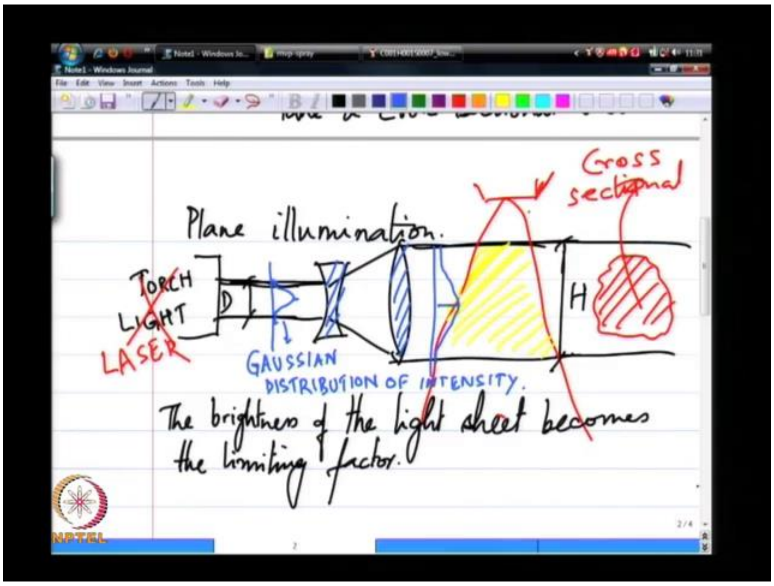

So, how do I take a cross sectional view? By looking at so called Plane illumination so I can take let us say torch light, that puts out a cylindrical beam of light of some diameter D and by the set of lenses create a height edge of create a light sheet that is of a some height edge and the thickness would still be equal to the diameter of the beam, but if I start with the beam that is of a very small diameter, I can create a essentially what looks like a rectangular sheet, the sheet of light that is of a triangular cross section.

Now if I use this kind of an illumination in a spray, I am only going to see the drops that are resident inside the spray. So, if camera in this particular view is normal to the sheet were our eyes are located currently then we would only see the drops as they propagate through this sheet of light. So, this plane illumination or light sheet illumination is a very nice technique to look at what is happening in a cross section now I could also illuminate I can have this spray, they were my eye is in which case I can create.

So, if I have this spray nozzles were my eye is I will essentially create a cross sectional view, either this way, either a meridian cross section or an axial cross section both are possible. The only problem with this kind of an approach really is that the brightness of the light sheet is quite limited; because you are unable to pack the brightness of the light sheet becomes a limiting factor. Therefore, most of these techniques while ever feasible were not really practical until the advent of the laser, the laser provided for a very nice way to pack a lot of energy into the beam.

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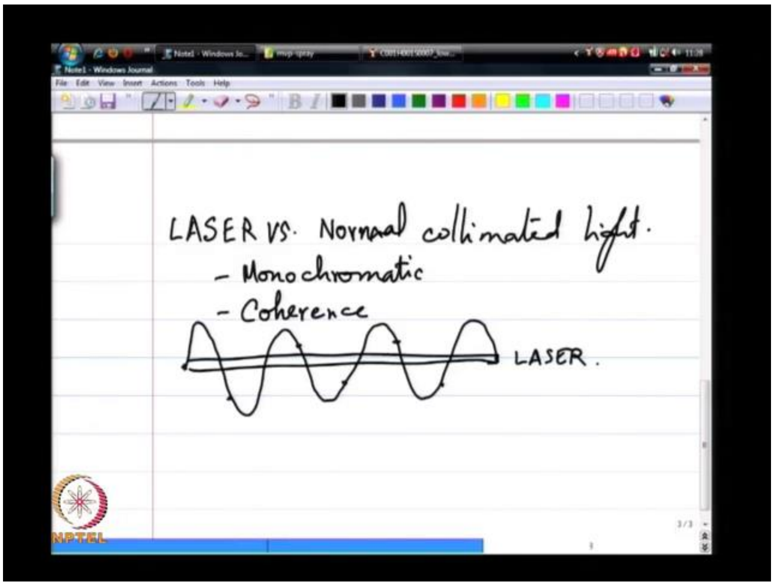

So, fundamentally what is different between a laser that puts out a cylindrical beam let us say a 1 mm diameter beam and a torch light that also presumably puts out a 1 mm diameter beam. So, let us quickly make some differences a call normal collimated light, collimated is where the light raises or all parallel. So, the first thing is laser is monochromatic, typically lasers are monochromatic that is all the photons that make up the light are of the same wave length unlike say normal white light illumination. Now you could also get monochromatic torch lights so to same, that are of very narrow wave length spread.

So, you can essentially have a monochromatic light source, but the biggest difference between a laser and in a normal light source is this idea of coherence. The fact that all the light that is being produced by the laser all the photons are in phase, that is if you imagine the simplest way to imagine this is look at light as an electromagnetic wave, that essentially for have a light beam, if I know the phase at one end of the beam, I know the phase at every other point because they are perfectly correlated, this is not true with normal monochromatic light.

So, if this is a laser, the wave that makes up this the electromagnetic wave that makes up this light is essentially entirely coherent in phase, because of which all of the photons that have produced are only adding to your light intensity, there is no destructive interference causing resulting in loss of light intensity in that for laser produces. Laser is the very nice source of illumination for photography in Videography like this phase.

So, if I create a light sheet just like is showed before, if this is now not a torch light but laser, I can create a beam of diameter D, now typically the divergence of this beam is usually very small, but it is not non zero it is the most laser beams do have small, but positive divergence fractions of (Refer Time: 13:47) radian usually, but the advantage is that it is a its a coherent beam. So, you can do a lot with coherent beams it you cannot do with incoherent light sources. Another feature of lasers is that it will always have a Gaussian distribution of intensity; the beam itself has a brighter in the middle than in the edges.

So, if I take a laser that has a Gaussian distribution of intensity and pass it though a pair of concave in convex lenses is just like shown there, that intensity distribution is still retained, the laser itself when distributed into a sheet would still be brighter in the middle here than at the edges. So, now let us go back to our video and look at how this can be of use to us. If I start of from some point over there, you can see that there are these white specs at this point where at the instance where I have paused the video, you can see that there are these white specs. Now those are presumably large drops that in this magnification look like white specs.

Now if I take another frame just short instant later, I can look at those same white specs that have moved a distance downstream. So, by knowing the distance that this specs have traveled and the time spacing between the two frames that I just used to illustrate this point, I can extract a velocity vector; however, the only problem with doing it in a video like this is that I do not know if they were all moving in a plane or they may have moved towards me and away from me. So, if when I do it with just diffuse illumination, like I have used to make this video I do not know the direction in which they have moved.

But instead if I had plane light sheet illuminating the spray then if the spec was visible in two successive frames; that means, it was inside that plane only. So, that becomes a precondition to extracting the velocity vectors, without which you do not know which way they move and so you are somehow your getting a component of velocity, but we do not necessarily know the exact plane in which they moved. Especially because with the lens that I had to make this video the depth of focus was fairly large, I do need that otherwise most of the spray would look just blurred and a very small part of the edge of the spray would look like it is in focus and that is not a very useful video to have.

So, if I want illustrate the points say the macroscopic measurement variables, I do need a fairly high depth of focus on my video, but if I do that I do not know which were the drops are moved.

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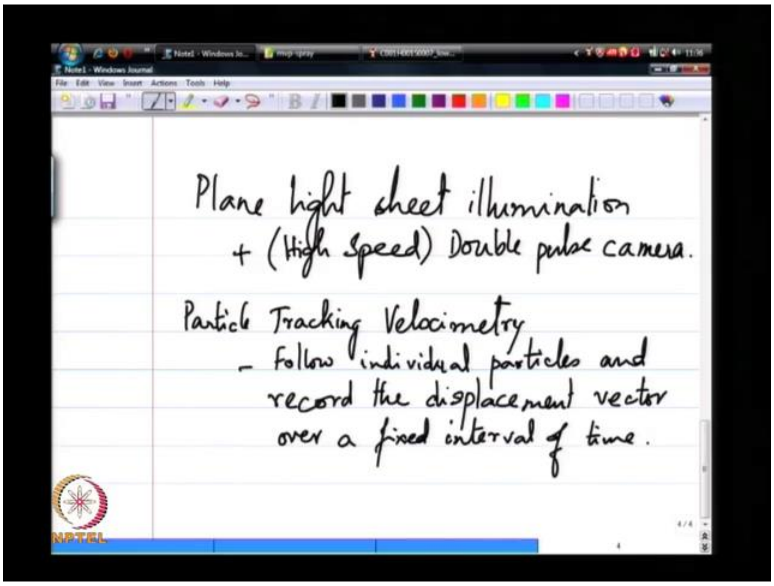

So, the solution to this is use a light sheet the plane light sheet, illumination plus a let us say high speed for an I put high speed in parenthesis, but high speed is not necessary, but what is necessary is double pulse camera, that is I need a way to take two successive snap shorts apart in time such that I know the time spacing between the two snap shorts. So, if I did that and if I went back a short distance, you can see this white specs, the let us some distance from the nozzle a short instance later all the white specs are moved and presumably if this was a plane illumination, then all of the distance moved by the specs are in the same plane as the illumination sheet itself and from knowing these two frames and the distance traveled we are able to extract velocity and this is called Particle tracking Velocimetry. This is the simplest of drop velocity measurement techniques, where you follow individual particles and record the displacement vector over a fixed interval of time.

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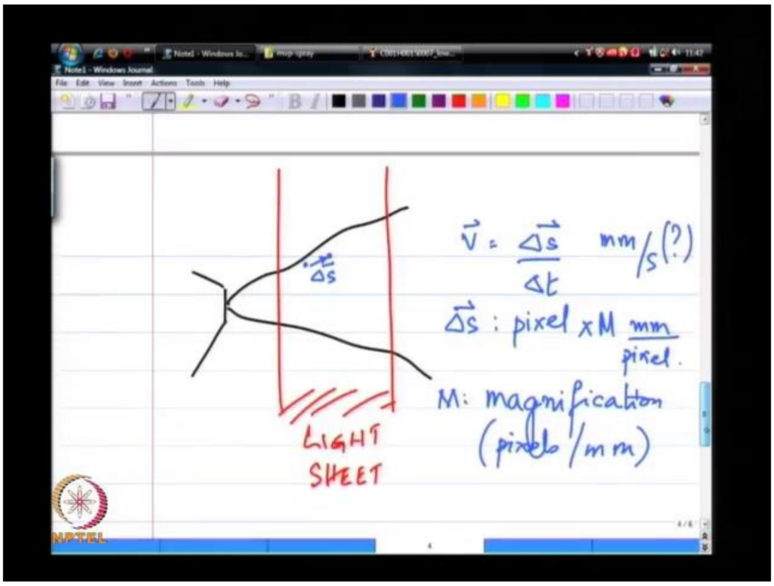

So, let us say I have a spray that I have used plane illumination. So, this is my light sheet, in my camera is where my eye is currently located.

So, in one frame let us say the drop was situated over here, in the next frame if this is the position of the drop, what I do now is that this is the displacement vector, the velocity is given by the displacement vector divided by delta t the time spacing between these two successive frames. Only problem with this is that when I take a video or an image like for example, will go back to the one we just from looking at this video, if you did know what a normal perfume bottle what look like do you have way of a extracting how big this spray is let see.

Let us take a simple example, let us have I take this frame, I can see the white specs close to the nozzle, move a short distance a short time later I know the position the new position of the specs, what I need is distance in milliliters or meters some length unit. A picture like this does not really convey length units; all I know is displacement in pixels because the camera works in pixels and in 3d boxes. So, when you have pixels all I know is that displacement in the x direction in pixel units and displacement in the y direction in pixel units. So, I have to a priory before I do this experiment have a way of figuring out how many pixels correspond to a length unit. So, that is called Magnification calibration. So, I need to calibrate this system for it is for its magnification. So, delta is in pixels, times magnification in millimeters per pixel. So, M is the magnification, in fact typically given units of pixels per millimeter, but we can also in; obviously, invert this and get the length per pixel, this is required before one can extract quantitative length based velocity information, otherwise all I know is some pixels per second.

Now how would be do this? We typically use a feature that is that is of an own length like in this case let us say I know some distance here, like the plunger diameter or a height a feature on a bottle like this that is that is known before hand and by counting a number of pixels that make up that feature where able to extract the pixels per millimeter. Now a lot depends on the kind of lens that is used in this kinds of photography and Videography, there are class of lenses that where the magnification is relatively uniform all around the image. So, if I do this kind of a pixel per millimeter calibration in one of the corners of the image versus the middle of the image, I will get a pixel per millimeter that is relatively the same, but I could there are other lenses which are as I go smaller on the focal length of the lens typically the magnification varies and across the image.

So, you are always better off with the very narrow angle of view lens, were the magnification are across the frame is relatively speaking constant; you know if you are otherwise constraint use a lens that has a very short focal length, then you have to have the pixel per millimeter measurement at different points in the image and use the actual pixel per millimeter at that location to extract the velocity measurement. So, in any case I do need this magnification in pixel per mm to convert displacement in pixels to velocity in length units let us say mm per second.

So, this is the simplest of microscopic parameter measurements. So, let us say if I want to measure drop let velocity, all I have to do is have create a sheet of light and look at the displacement of the pixel in the plane of the light sheet and that gives me the velocity vector in the plane of the light sheet. If the drop was moving perpendicular to the plane, if it had a velocity perpendicular to the plane I would not be a able to measure that velocity component from this kind of a measurement. Now if the drop did have a velocity component perpendicular to the light sheet, there is another thing that could happen that I could see the drop in the first frame and actually not see the drop in the second frame, it just disappear. So, I would not be able to measure the displacement of that drop. So, if I have to measure the displacement, it has to be present in both the individual frames that are sometime a part, for me to be able to extract velocity vector information.

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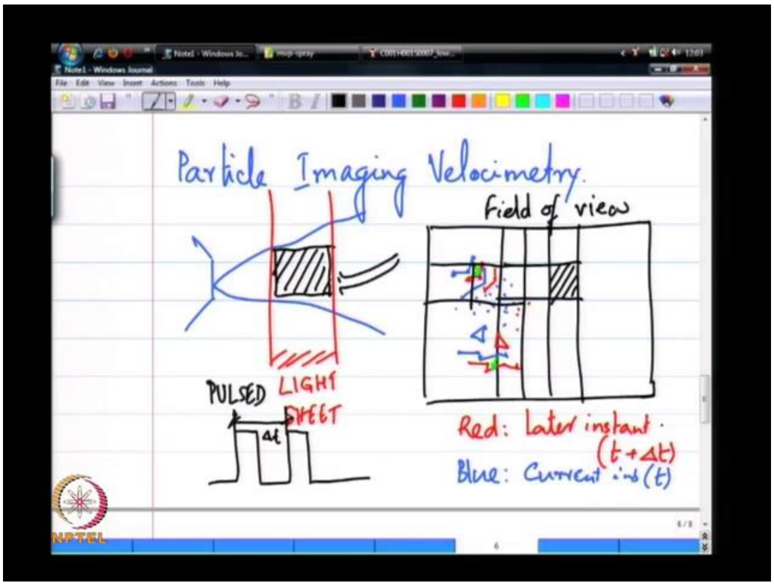

So, this is the simplest of drop let velocity measurement techniques, we will extend this now the only problem with this is this. If you look at what is happening like very close to the nozzle, I just have a little grey scale image. So, if you look at this particular region here, I can see this specs of white light or I could down here I can see this specs of white light, but for the most part of the spray close to the nozzle, especially I do not see individual drops I see like a speared image were I am able to make sense of a group of drops, like for example, if you take a region down here, I see that there are drops, but it is not where I am able to clearly follow one bright spec and look at displacement of a spec.

So, in other words if I look at if I focus my attention down in a small rectangle were I am pointing right now, and look at an image now which is frozen and the short time later, I cannot follow individual drops they all look alike in this image I am I cannot follow individual drops, this is going to be the case in most of the spray; except in the very periphery of the spray were I see flying drops or except in the middle of the spray where I see bright specs occasionally coming out. These are large drops that I can mark; except when that happens most of the spray is going to look like a grey scale image with little dots and I need to get velocity information from that. In order to do that we have to move to an algorithm to a technique called particle imaging Velocimetry, the hardware part of a particle imaging Velocimetry is still the same that I have a spray, that I have a light sheet illuminating the spray and I have one camera where my eye is located right now and from that we get an image.

So, let us say we are going to image this part; I am going to draw it out in a bigger rectangle on the side. So, this is my field of view. Typically on a camera that is used for these kinds of applications, we want the depth of feel to be very small. In fact, there is no need to see drops that are outside the liquid sheet, all I want is the depth of focus of this imaging system to be approximately equal to the thickness of the light sheet, I do not need much more of a depth of focus to the lens and the camera system. Now in this field of view I have these specs of light, presumably coming from the drops. So, the technique that is used here since; let us say if I take the drops are in the shown pattern and sometime later let us say the drops are all like this, you can look at sought of the arrangement of the red specs as I have shown.

So, let us say red is a later instant of time, sum t plus delta t and blue dots are current instant which we call t. So, the blue dots were obtained at time t and the red dots were obtained at a time t plus delta t. If I look at the relative arrangement of these dots, I am just to show you the I am going to draw this kind of a like a star constellation just to illustrate the point if I do the same thing with the other one, you see that there is a designable arrangement to this drops.

So, if I take a cluster of drops not really follow an individual drop because the two the drops all look alike, that when I take two snap shorts I do not know which dot in the second snap shot corresponds to which dot in the first snap shot. But I can look at their relative arrangement of these dots, say for example down here if I take these 3 dots, there is a cluster arrangement like that if I take these 3 dots there like this. So, there were 3 drops in that first image that were arranged sought of in this angle, in the second image I can now recognize this feature even though I was not able to relate this drop to that drop, I can now look at the displacement of this feature not necessarily the displacement of a drop, this is essentially what particle imaging velocity cemetery is.

So, if I know look at this feature here, I can draw a velocity vector in that direction. If I look at this feature here I can draw a velocity vector in this direction. So, this is the basic technique that is that is utilized, now how is it applied practically? Practically what is done is to first segment this image into smaller regions and will take one segment of this field of view will do a same blue and red.

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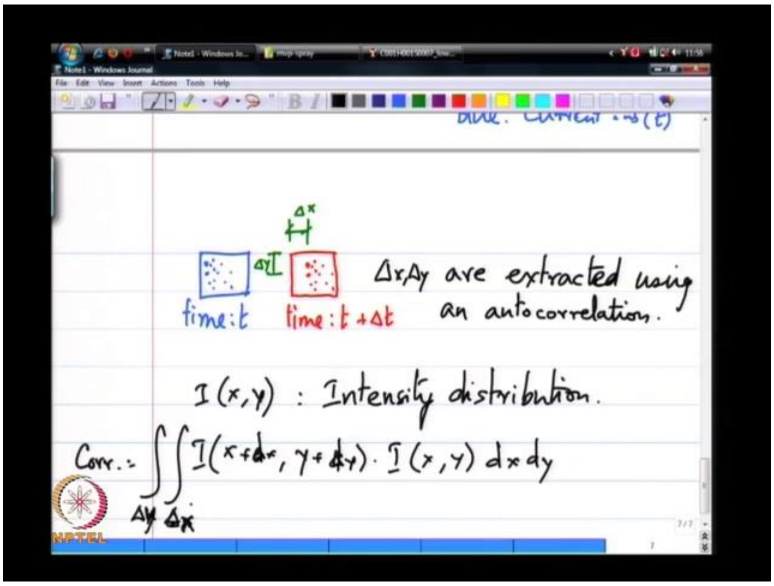

So, let us say the blue dots were all sought of like that and the same the same segment of this image, if I take if the drops were towards the left edge of the segment the way have drawn them and this is the image at time t and this is the image at time t plus some small time delta t. So, if I now take the drops were all and one sought of one part of the image to the left edge of this segment and all of them have essentially sought of move to the right edge of the image and I want to now look at how much is the displacement.

The way this is done is I take the time instant, I take the segment at time t plus delta t and move it over to the image at time t and look at the amount of displacement that I have to make to the image both delta x and delta y. So, how much if I take the image at time t plus delta t and this is my image at time t let us say I will use my 5 figures to sought of illustrate the idea of the relative positions being a same. So, if this is my first image and if this my second image, I know I have to move it up about that much and move it to the left about that much to get good coincidence. Now it is possible that some of the relative orientations have moved.

So, if the drops while they were like that in the first image, may have sought of moved slightly in the second image. But when I do this on average I am going to look for a displacement in the y direction and x direction that will give me good fit of the second image on top of the first image, this process is mathematically called an Auto correlation.

So, delta x and delta y, what does this do? Essentially if inside this pixel, I have and I or x comma y which is like a an intensity distribution, you could imagine this as a this being a grey scale distribution and if I take I x plus delta x and y plus delta y times I x comma I y. So, this is basically a correlation function of the auto correlation function of I over a distance where I go on d x a distance delta x or delta y and then delta x here.

So, this as I bring these two images closer and closer to each other, I do reach a point where the fit basically increases and as I go passed in the point where they seem to match the fit parameter decreases again. So, this is the correlation coefficient initially increases and then decreases. So, we choose the point corresponding to delta x and delta y, that gives us the maximum value of a correlation parameter, so even though one or drop may have moved. So, I can have this general arrangement of drops that has been displaced, but in a stretched fashion slightly starched fashion, will still be able to pick out the point where the correlation coefficient take on a maximum.

So, this correlation coefficient taking on a maximum, gives us the displacement in the x direction back towards original image and the displacement in the y direction back towards the original image that gives us the best fit of the first image over the second or the second image over the first, so from here once I know delta x and delta y and knowing the magnification. So, this delta x and delta y will still be only in pixel terms and after knowing the physical magnification of the system, we can extract a velocity component in both the x and y directions.

Now so this is the basic principle of operation of a PIV. So, if I look at particle imaging velocemetery, it is essentially two images that we are trying to correlate with each other and from the maximum peak that occurs in this auto correlation function. So, the auto correlation function will call this alpha, alpha in this particular case is the function of delta x and delta y. So, the way I have defined this auto correlation function were going to choose a peak in alpha, in both delta x and delta y, that is essentially the principle of operation. Practically the way a PIV system is usually implemented, we do not take two pulses to images with the camera flashing twice or the camera sought of acquiring two images, it is usually done by using a pulsed light sheet.

So, you can imagine the camera is on all the time, but we have a light sheet that is illuminating a cross section of the spray and that light sheet is turned on and off and on again and off again. So, if the pulsed the light sheet intensity fuel is of that kind and by knowing time spacing between arising at due to the two pulses, we are able to estimate the velocity, we are able to essentially take two images, but they are essentially two images of some moving object, but in the same frame. So, if I take the field of view, I will have the blue pixels and the red pixels, the blue dots and the red dots all in the same image; now you have to imagine that there is really no blue and red there is just grey, but they are all in the same image.

So, you take the image and you take each segment and move each segment over on to itself until you get an auto correlation peak and you do this with each little segment. So, it is essentially the same segment, it is like have taken two frames and added them together. So, I am going to see like a duplicate of each frame, just like I have drawn here with the blue and the red dots, but the blue and red dots will all beyond the same frame.

So, if I took this say for example, if those are the blue dots, these are the red dots and if this is one of the frames, we are going to move this segment over on to itself until we get an auto correlation peck, moving it both in the x and the y direction. So, that gives me essentially this displacement delta x. So, it is advantages to pulse the laser sheet and not pulse the camera because we can get much faster pulse frequency the laser with the pulse laser then you can get with the camera.

The primary bottle neck there is if I have a high speed camera, a camera is usually got a sensor the old camera is had what is called a CCD sensor array, which is called a charged coupled device sensor array, the newer once are what are called C mass metal oxide sensor arrays, that once an image is acquired that data has to be dumped into a ram location emptied and then you have to acquire a new image. So, this time spacing between when the image can be dumped into a ram location and readied for the next frame is too long for most PIV applications. So, you leave the camera on all the time, but pulse the laser. So, you have two images that are successive snap shorts, but you do not know you cannot tell one image from the other because there all part of the same frame. So, I can now move individual parts of this frame over on to itself until I get a high correlation peak. So, this technique this is how PIV is practically implemented in a real system.

We will continue this discussion in the next class, were we will talk about other non intrusive techniques starting with the LDV which is the Laser Doppler Velocimetry system and then PDPA which is called the Phase Doppler Particle Analyzer. So, that is now going to get us into the realm of being able to measure drop sizes.

We will stop here; will continue this in the next class.