**Optical Methods for Solid and Fluid Mechanics**
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**Lecture - 21**
**Particle Image Velocimetry VI**

Hello and welcome back. So we are discussing particle image velocimetry techniques and we have discussed quite a bit on image processing issues related to that. Today what we want to do is we want to look at some of the issues that come up after post processing, right?

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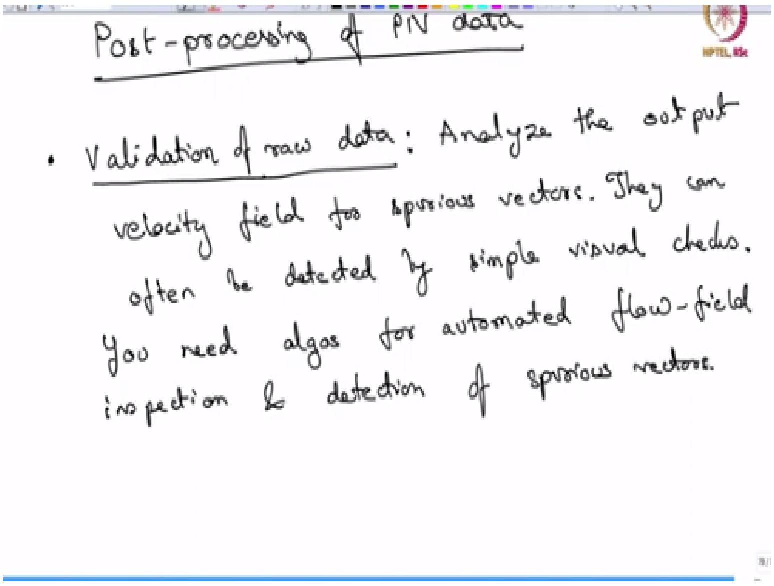


We are going to look into the post processing of PIV data, okay? Now once you do the do the image analysis and you get a velocity field, you must do validation of raw data. So you will get an output from your software and but you must check it right, so that is what validation means, validation of raw data, which means that analyze the output velocity field for spurious vectors..

I will explain what spurious vectors are, they are errors in calculation. They can often be detected by simple visual checks. However, even though sometimes visual checks can be done, you do need algorithms which will detect these things automatically. So you need algos, algos stands for algorithms, for automated flow-field inspection and detection of spurious vectors.

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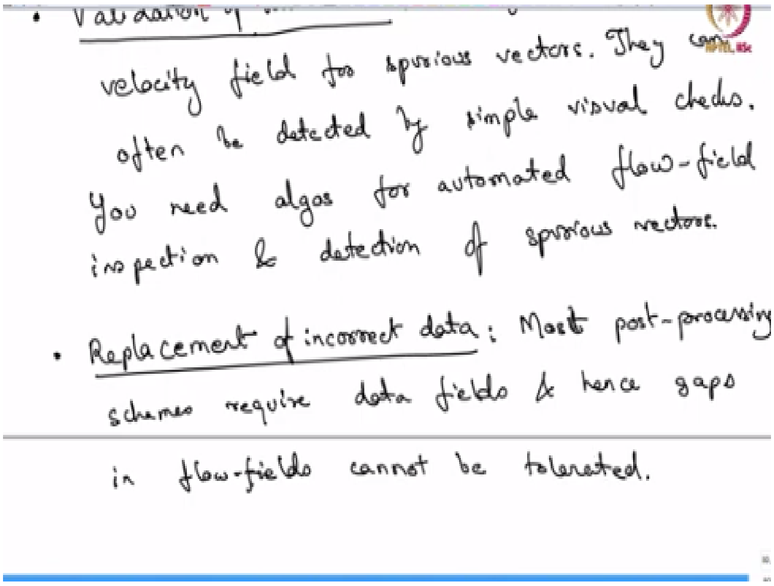


You also then need techniques to replace incorrect data. So just figuring out a validation is not enough. Replacement of incorrect data is often required. And this is so because most post-processing algorithms, most post-processing schemes require complete data fields. For example, if you are calculating whether continuity has been violated or not you cannot work if certain data points are missing.

You need the entire data field and hence in such and hence gaps in flow fields cannot be tolerated. We are not going to go into all these different aspects because that is, but we are going to discuss some of the issues right?

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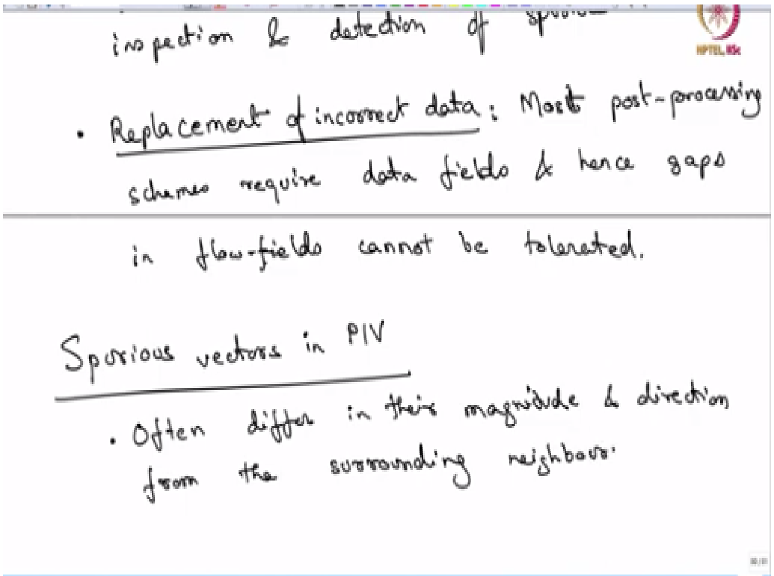


So the issue is that we want to discuss is the case of the spurious vectors in PIV, okay. Now spurious vectors are basically incorrect vectors and they often differ. So these are incorrect vectors which they often differ in their magnitude and direction from the surrounding neighbors. And we will give you an example. I have given already, shown you some things last class. We will go back to that slide just to try and see it again.

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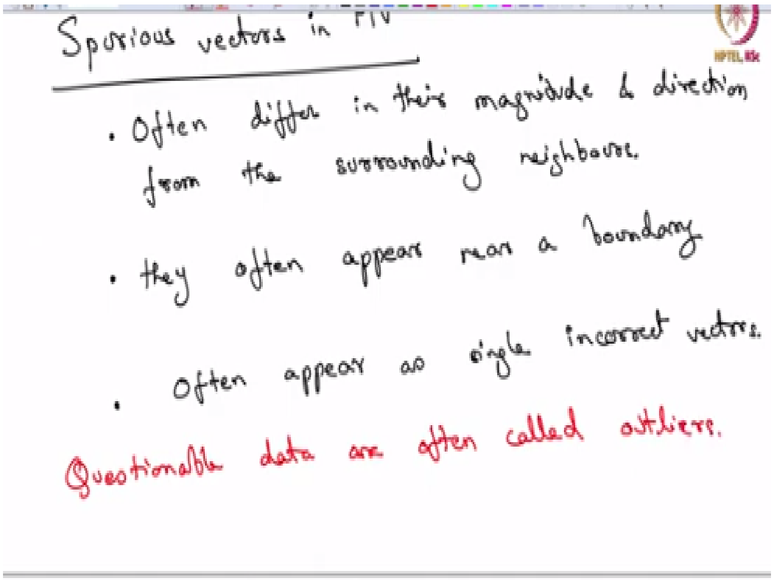


And they often appear near a boundary. The boundary can be of edge of a flow-field, it could be edge of a illuminated region, something of that sort and they often appear as on not always but sometimes they appear as single incorrect vectors. So to detect spurious vectors first you have to detect what are called outliers. So questionable data are often called outliers. So we have seen some example last time okay, wait a second.

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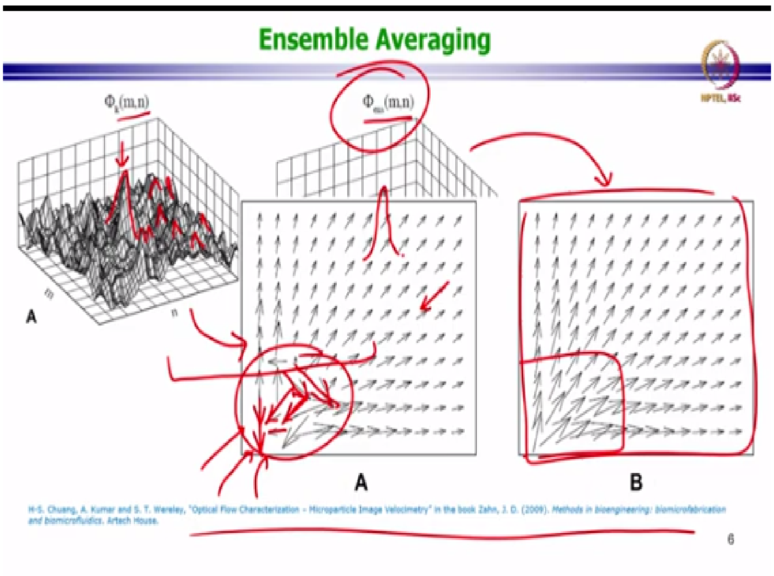

So if you remember recall this particular slide, we had said how the use of the ensemble correlation peak helps remove incorrect or spurious data. And in this case, you could see that you have the flow-field looks very straightforward, looks like there is a source type flow or something flowing out from this corner and going in different direction, but suddenly you have a line here, which is very long.

You also have flow reversal all of a sudden in this case, and these seem to be spurious vectors, right? So an algorithm which can detect this and replace them with correct vectors. In this case, it was it was resolved through the use of the ensemble averaging. But this is a special case and cannot be used always. But you do have errors like this sometimes. And you can also have a situation where the flow field looks very nice and smooth.

But all of a sudden you will have one velocity vector pointing in the opposite direction. So that is automatic case for trying to evaluate whether that is an outlier. So you need techniques for that. There are many different methods which can detect outliers.

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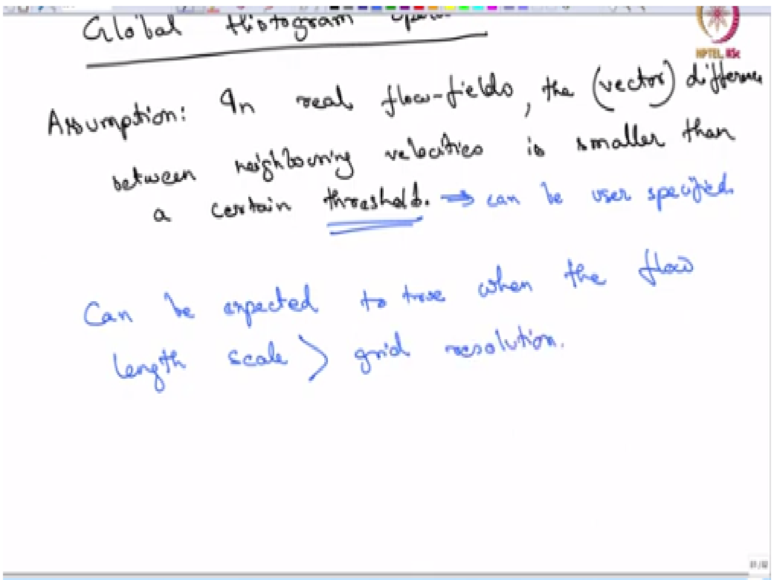


I will just discuss a couple of them. One of them is also called a global histogram operator. Here the assumption that the built in assumption is that in real flow-fields the vector difference, the difference between neighboring velocities is smaller than a certain threshold. This certain threshold is something that can be a user defined threshold. Many softwares, commercial packages already have built in numbers.

So you have to, if you are using one of these you have to be careful in what the software is already implementing. So the threshold, this can be user specified, okay? This can be expected to be true when the floor length scale is much bigger than the grid length, grid resolution, the floor length scale is greater than the grid resolution. To implement such method, what you have to do is, okay maybe I will go to the next slide.

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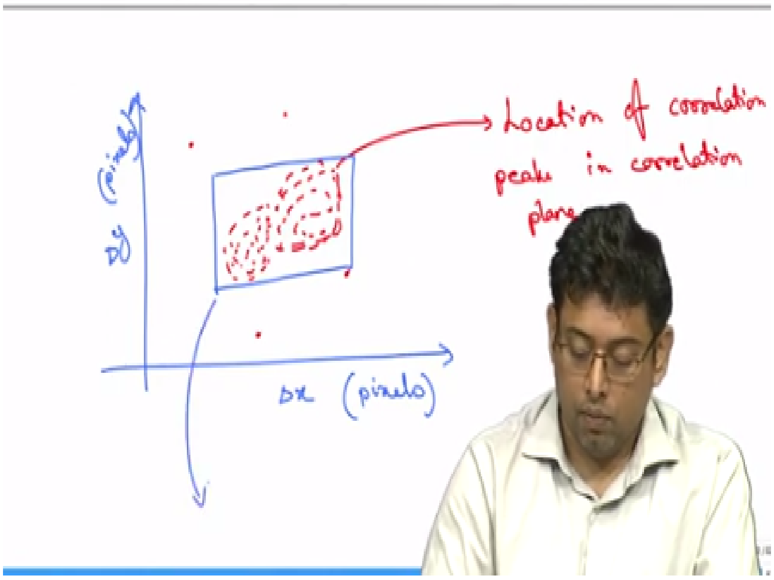


And you have to as the name suggests, we will first plot something, okay? In this case, what we are going to plot is take the raw data and we will plot let us say delta x which is in pixels and delta y which is also in pixels and we will plot the location of the correlation peak in the correlation plane. So every time you evaluate a correlation peak there is a delta x and delta y right, which you are again using to calculate evaluate velocity.

So you plot all the delta x's and the delta y's that you have gotten in the correlation peaks, right? So I am just going to draw an imaginary situation where let us say you have points which have occurred something like this, okay? So all the points are distributed something like this. And I just wanted to clarify so each of this is the location of correlation peak in correlation plane, okay?

And then suddenly you also have some data points which are like this. Now see you have all the rest of the data distributed nicely and then you have these some points which are lying very much outside. So what you can do is in this case you can draw a rectangle and say okay anything that lies outside of this rectangle seems to be outside of a certain threshold and I am going to reject it.

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So you draw this, so all displacements outside of this boundary are to be rejected, okay? So this is one way.

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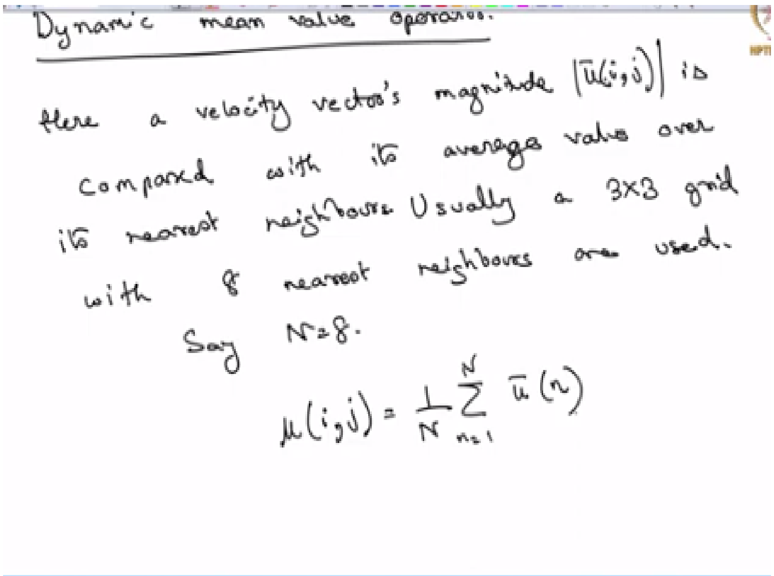


There is another method which is also called the dynamic mean value operator. Now in this technique here what we do is here a velocity vector, so the magnitude of a velocity vector, so here a velocity vector's magnitude which is basically nothing but this quantity u (i, j) is compared with its average value over its nearest neighbors. And usually what you can do is implement let us say 3 cross 3 grid around the velocity vector.

So usually a 3 cross 3 grid with 8 nearest neighbors are used. So say N = 8. Then what you can do is you can define an averaged quantity of all the different velocities over this 8 number. So you take some dummy variable here small n going from 1 to capital N. And you average over all the different grid points that you have.

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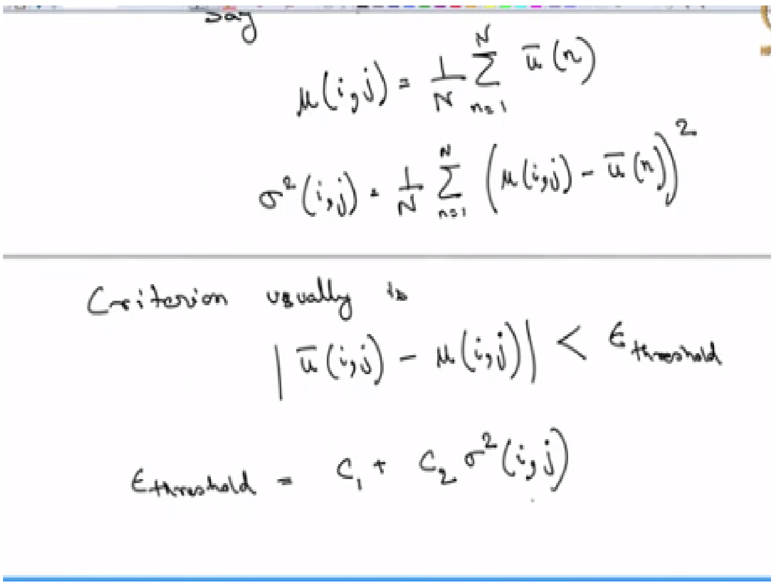


And then you also define these quantities sigma square i, j as 1 by N summation n equal to 1 capital N. And then you have your mu (i, j) minus, okay? So you define this quantity and then you implement the criterion, usually is that my u (i, j) at a given location minus this average quantity which you have evaluated over 8 neighbors. This is less than some epsilon threshold.

And you can define a dynamic epsilon threshold so which is why the operator gets its name from as some c 1 plus some c 2 sigma square. So my epsilon threshold is not just a passive value but has a strong dynamic component to it. So once you implement this kind of error methods to catch spurious vectors you can remove spurious vectors from your system and you will be able to get a corrected velocity field.

Then finally then what you have to usually do is if you have such a system or if you have spurious vectors, then you have to finally replace them and replacing is still easier. What you can do is if you have only hopefully the whole thing has gone well and you have only had to replace a very small number of velocity vector. So maybe one or two vectors in 100. So 1% or 2% rejection.

In that type of situation what you can do is use interpolation. So you already have velocity field and then use interpolation to calculate the new velocity. So wherever you have gotten rid of the velocity vector, you calculate the velocity vector at that grid location using an interpolation scheme. So this is what most commercial softwares will also do and help you get the final data.

So we have discussed the issue of PIV in quite a bit of detail, which is again a quantitative technique as you have already seen, you end up getting a very, you get a number associated with a velocity field in your case, right? So it is a quantitative full field technique. There are also other optical methods which need not be as quantitative as particle image velocimetry, but they give you quite a bit of insight into fluid flows. So we are going to show you some of them in a lab demo.

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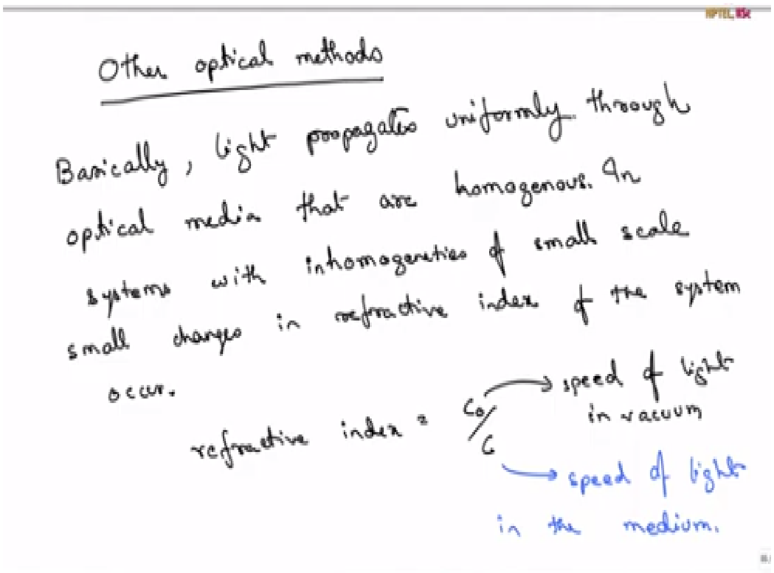


But I just wanted to have a small discussion about other optical methods. Now basically techniques such as shadowgraphy and Schlieren, what they do is they use the idea that light propagates uniformly. So light propagates uniformly through optical media that are homogenous, sorry that are homogeneous. But when light encounters inhomogeneities then the speed of light changes in some sense in relatively in these cases.

So in systems with inhomogeneities of small scale, small changes in refractive index of the system occur, right? Now if you recall our refractive index is defined as C naught by C where this is the celebrated universal speed limit of light in vacuum. So this is speed of light in vacuum and this is the speed of light in the medium.

Now these differences of refractive index that can occur in, that can occur for systems which have these small inhomogeneities, this need not be very high. So the difference that techniques like shadowgraphy and Schlieren exploit, there the differences are often very small. They can even be as small as the third and the fourth place of decimal and that is good enough for creating changes in, strong optical changes which are reflected in the images.

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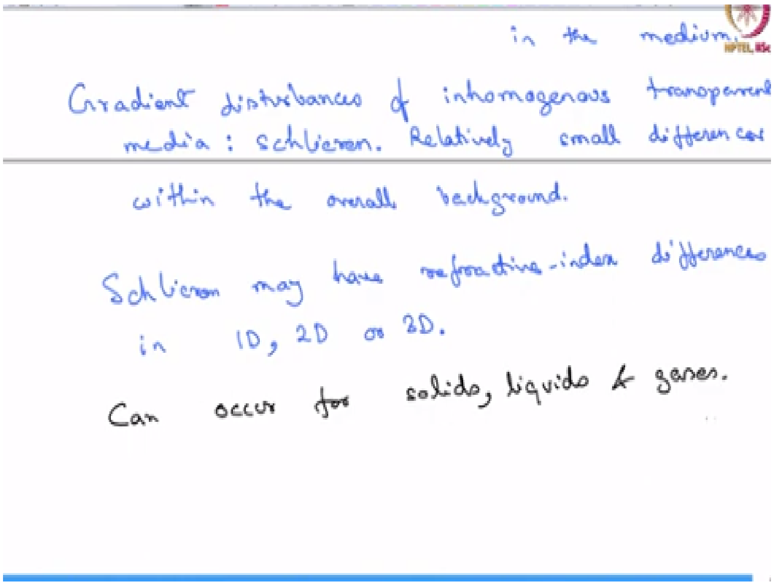


So here I will try to introduce a word called Schlieren, which I will say that the gradient disturbances of inhomogeneous transparent media are called Schlieren. They are relatively small differences, relatively small differences over the background. So we are not talking about very large differences, very small differences over or within the overall background.

So Schlieren differences may be of, so they can be of Schlieren differences or rather Schlieren may have, okay **(FL)**. So Schlieren may have refractive index differences in 1D, 2D or 3D, okay? And this can occur, and can occur for solids, liquids and gases. So the overall idea is that you will have a situation where perhaps a flow is being created, which is causing an inhomogeneity of the transparent media.

Because of that inhomogeneity, there will be small differences of refractive index between different points of the system. And these small differences need not be very high. As I have already said, they can be very small of the order of the third and the fourth place of decimal. And these differences can be in 1D, 2D or 3D.

Obviously the, if it is a three dimensional situation, then it is difficult to image usually or want to have a situation which is either one dimensional or two dimensional for it to be able, for you to be able to image them like that. And this can occur for either solids, liquids or gases.

In fact, some of the first applications of secular and imaging was for solid systems. Now these type of Schlieren differences, they can be exploited by different optical imaging techniques. One technique is shadowgraphy. The other is called Schlieren imaging. Now shadowgraphy, as the name suggests, it is actually very straightforward. You utilize the shadow of an object.

The differences in fluid flow being that you are imaging a transparent system. So the differences that are very small differences in the refractive index, it is not a case of a solid obstacle in front of a flow, but rather in the flow itself, there will be small differences that are created of refractive index due to small inhomogeneities and that is used and amplified in a shadowgraphy image to give you a good image.

But shadowgraphy images are not a focused image. So they are not supposed to be a one-to-one correspondence, not supposed to be not in one-to-one correspondence with the actual object. So quantitative evaluations with shadowgraphy are sometimes difficult, but they can yield very strong insights, qualitative insights into the nature of the flow.

Whereas Schlieren the way the Schlieren imaging is usually implemented today, it what it does is it essentially creates a focused image of the actual object which is the image is a conjugate of the object itself. So there is a one-to-one correspondence between the object and the image. So you can actually use Schlieren images for qualitative evaluation. So just we will write this down.

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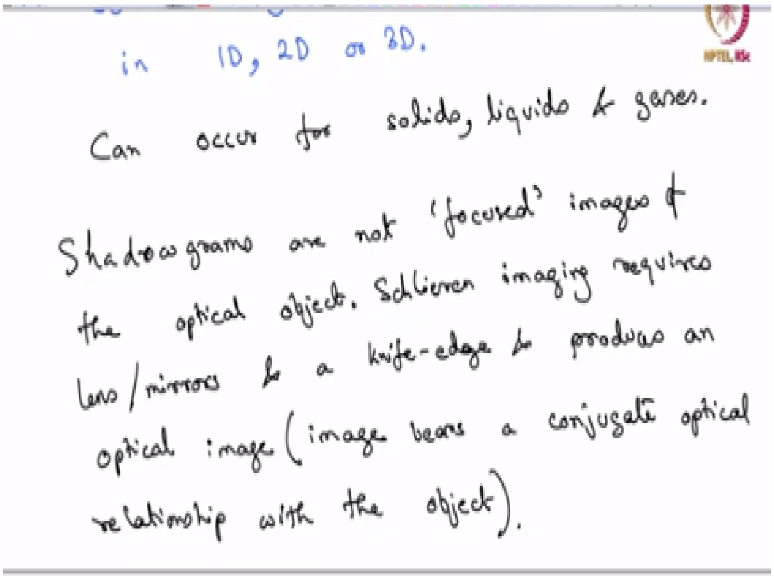


And shadowgrams are not focused images of the optical object. However Schlieren imaging requires either parabolic mirrors or requires lenses/mirrors and a knife edge. So it need not always be a knife edge, but something to block off images, so basically a blocker and produces an optical image. Meaning that the image bears a conjugate optical relationship with the object, okay.

So that is why Schlieren imaging is often very much preferred over shadowgraphy.

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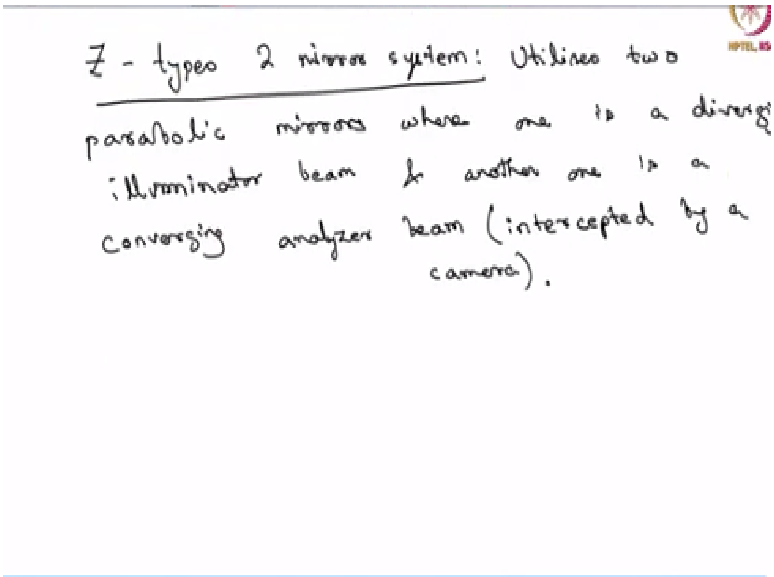


Now you can have different types of Schlieren imaging. One is also called the Z-type two mirror system, which is what we are going to see in one of the lab tours that we will give you. So there are different types of systems possible using lenses or mirrors.

One of the most popular one is called the Z-type two mirror system. And the reason I am telling you about this is because that is what we will see in the lab in the next class.

So I am just going to introduce you to that. So it utilizes two parabolic mirrors where one is a diverging illuminator beam and another one is a converging analyzer beam. And this is, the analyzer is what is usually intercepted by a camera, okay?

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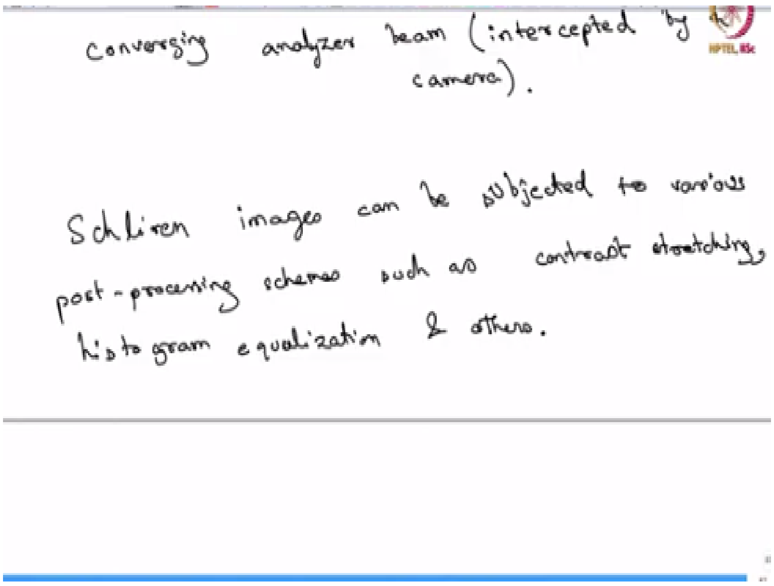


So now Schlieren imaging because they are Schlieren's images can be subjected to various post processing schemes such as contrast stretching, histogram equalization and others, okay? So the only thing you must take care of in the post processing of Schlieren images is that the image should not become distorted.

But there are many image processing schemes which can make sure that you enhance the image quality without distorting the image. And after you are done with that, you can still use even more sophisticated methods to get very clear data out of that. So Schlieren imaging is usually extremely preferred and over shadowgraphy.

And what we want to do now is in the next class, we want to give you an overview in the lab of these three techniques that we have discussed here. And one being shadowgraphy, the other being Schlieren imaging, and the third and the final and the most important will be the particle image velocimetry.

So out of all these, particle image velocimetry stands out because it gives us very quantitative data about the flow field. But Schlieren and shadowgraphy are still very popular, because they do give, they can give a strong insight in certain cases. And we will see what those are, some examples of what those are in the next class. So I will end here today. And thank you very much.