Experimental Methods in Fluid Mechanics
Professor Pranab Kumar Mondal
Department of Mechanical Engineering
Indian Institute of Technology, Guwahati
Lecture 33
Use of PIV Contd.

Good afternoon, we will continue our discussion on PIV measurement technique, and in fact, in the last lecture, we have discussed about the cross-correlation algorithm, and we will see, what is cross-correlation algorithm and why it is having advantageous features in comparison with the auto-correlation algorithm.

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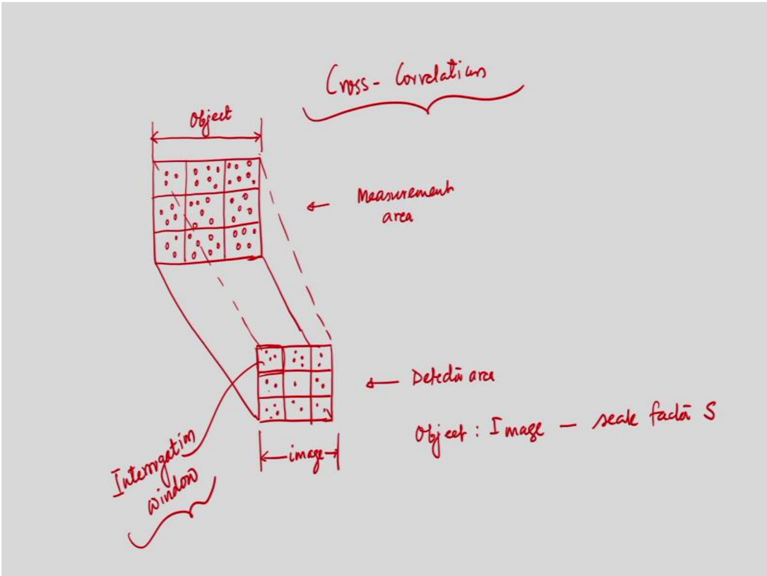

So, in the last lecture, we have discussed about the image capturing technique and from there, from the captured image we need to correlate, so that, we can obtain the velocity of the particle, and if we can predict the velocity of the particle, then from there, we will try to predict the velocity of the fluid, and that is, what is the objective.

So, if we need to know little bit more about the cross-correlation algorithm, we need to know schematically, that image which is captured from the object, from the measurement area into the detected area, and I would like to draw the schematic again, which will help us to understand the algorithm.

So, that is the, say this is the, and we have the particles, now this is the measurement area and this is the object so, this is object. Now, we will get the detected area that is the image. So, this is the image and this is the detected area. So if we so, this is the detector area. Now, we will have particles so this is the detector area and we have defined that object to image are scale factor S.

So, we are focusing a particular zone in the flow field. That is the zone of our interest, rather we are illuminating using light, and we are capturing the image from the object and that is the detector area. Now, we have discussed that the images, which we have captured are divided into rectangular windows which are known as interrogation windows. So, these small windows are the interrogation windows.

So, image which is captured, so these are the interrogation windows so this is interrogation window. Now, there will be two different methods, that is what I have told, that is known as Auto-correlation algorithm and Cross-correlation algorithm which are used to predict the velocity of the particle, seeding particle. So, we will now write what is the cross correlation algorithm.

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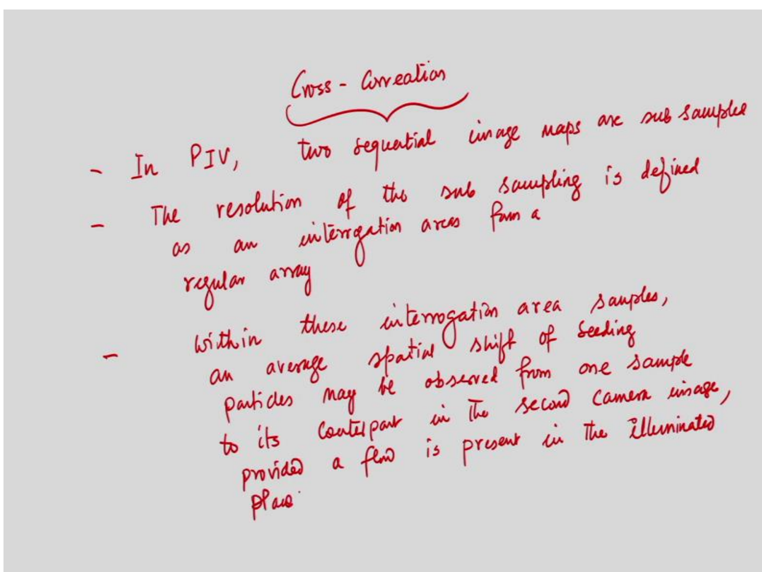

In Particle Image Velocimetry, two sequential image maps are sub sampled. So, in PIV, two sequential image maps are sub sampled. I will discuss in detail again, and the resolution, the resolution of the sub sampling is defined as an interrogation areas from a regular array. So, the resolution of the sub sampling is defined as an interrogation areas which forms a regular array.

Now, next is, which is very important, within these interrogation area samples, an average spatial shift of seeding particles may be observed from one sample to its counterpart in the second camera image, provided a flow is present in the illuminated plane. So, this is very important. So, this is the basic of the cross-correlation algorithm that means, in PIV two sequential image maps are sub sampled that is, the first and two, first frame and second frame.

The resolution of the sub sampling is defined as an interrogation areas and which forms a regular array we have discussed in detail in the last two lectures. Now, within these interrogation areas samples that when you are doing sub sampling, an average spatial shift of seeding particles may be observed from one sample to its counterpart which is present in the second, second camera image, provided the flow is present in the illuminated plane.

So, we are illuminating flow is present in the illuminating plane and what is done, from this sentence it is clear that where, image maps are sub sampled and we are considering the interrogation area samples and average spatial shift of the seeding particles may be observed, and the spatial shift is observed from where, from one sample to its counterpart in the second camera image, and we have to ensure that the flow is present in the illuminating plane. So, this is what is the basic of the cross-correlation algorithm.

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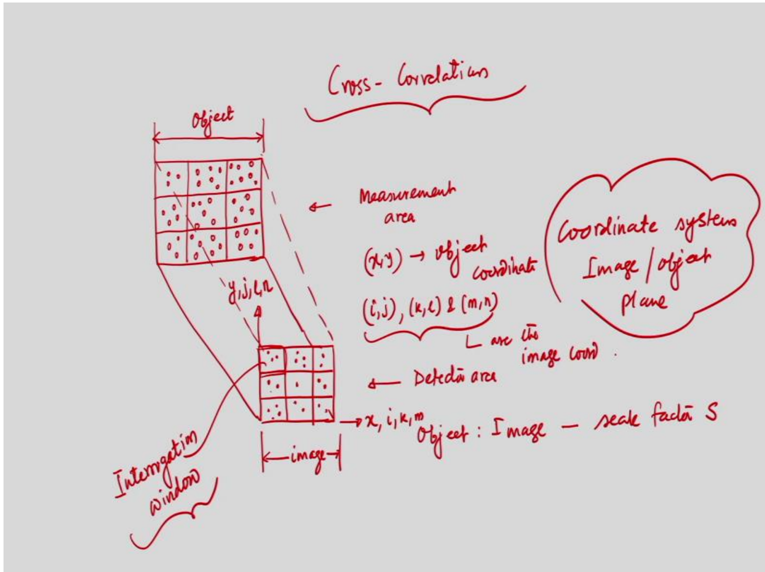

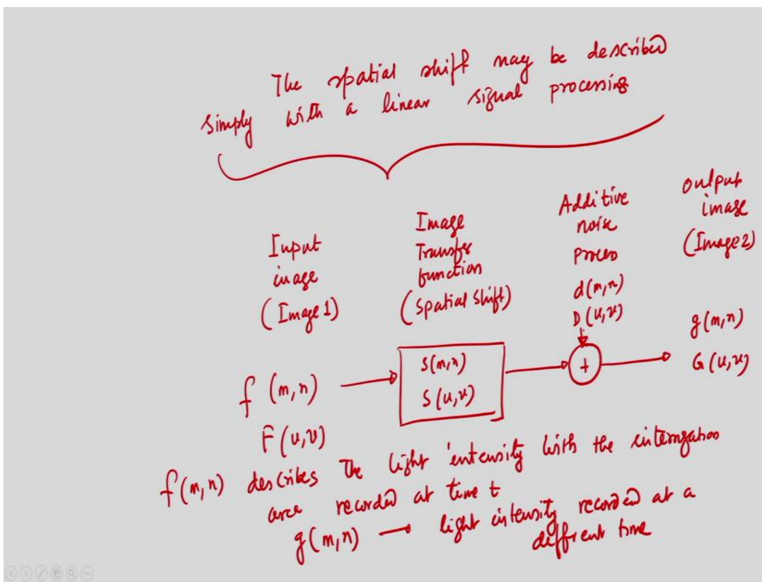

Through a block diagram, the spatial shift, the spatial shift, may be described simply with a linear signal processing. So, if I show, that input image, that is image 1, then image transfer function, spatial shift, additive noise process, output image that is image 2. So, the spatial shift that is what I was telling, the spatial shift of the seeding particle may be observed from one sample to its counterpart in the second camera image, provided the flow is there in the illuminating part.

So, the spatial shift may be described simply with a linear signal processing, that is, image 1, image transfer function, additive noise process and then we will get output image. So, say this is f m comma n, this coordinate system that is what we have discussed in the coordinate system and image object plane. So, this is x, this is y. So, this is x, i, k, m, y, j, ij, kl and mn, where x, y for the object coordinate, object coordinate and i, j, k, l and m, n are the image coordinate.

So, these image coordinates are measured in pixel and object coordinate in the SI system. Now, so, that means, f m comma n that is the, I am writing f m, n that is f function u v, that will be now taken into the s m comma n that is s u comma v image spatial shift, then we will have this additive noise d m, n, capital D u comma v and finally, we will get g m comma n that is G u comma v.

So, this f m comma n that describes, describes the light intensity within the interrogation area recorded at time t and function g m comma n, this is the light intensity, recorded at a different time. So, this is, the spatial shift that we have tried to understand through this block diagram, that means, m comma n, mn, ij and kl these are the image coordinate.

So, the this f m comma n, that describes the light intensity with the interrogation area recorded at time t while the g m comma n, that is also the light intensity which is recorded at a different time. Now, image transfer functions see there is special shift and the basic is the additive noise that will be there. So, this is the additive noise that should be addition and they are with the output image.

So, what is the important point, that means, within these interrogation areas, interrogation area samples, so, we are sampling, sub sampling, there will be an average spatial shift, spatial shift of what? Of the seeding particles, and the average spatial shift of a seeding particle may be observed from one image or one sample to its counterpart in the second camera image.

And we need to ensure that the flow is present in the illuminating plane because continuously flow will be there otherwise, how can we ensure. So, the flow is continuous, we are focusing, you are illuminating a particular part, particular zone in the flow field and in that particular zone continuously flow will be there. So, we are focusing the light, first light, we are capturing image, again we are focusing the light, we are capturing second image.

But we have to ensure and we are dividing the image into number of windows and that is, that is the interrogation areas. So, we are and then we have to sub sampling. So, we have to assume that the images which are captured during first frame and that image will have spatial shift and spatial shift is there, that means seeding particles will have a spatial shift.

So, the spatial shift of the seeding particles may be observed from the first sample, from one sample to its counterpart in the second camera image. And since there is a continuous flow, and we have to ensure that there will be flow in illuminating part. We will discuss this aspect again in a greater detail when we will be discussing about the micro PIV measurement technique.

So, if we use micro PIV technique to measure, to characterize the flow, to measure the flow, in the region of load or somewhere then I will see that, this micro PIV provides a very good. micro PIV analysis provide that very good I can say measurement technique, measurement platform, wherein we can characterize, we can characterize the flow velocity, flow field in a more accurate way.

So, we will discuss this algorithm again, but at least today, we will try to see that, if we try to recall, in the beginning of this class we have, we told that, we have discussed that the auto-correlation algorithm is also available and the cross-correlation algorithm is also available. But, but between if we compare these two algorithms, then in most of the cases, cross-correlation algorithm is used.

So, why cross-correlation algorithm is used and in most of the cases that means the auto-correlation algorithm is having a few important, I can say disadvantages, not important, but a few disadvantageous features and because of which the auto-correlation algorithm is not popular. So, now time has come to understand at least to compare what is to compare the issues between these two methods and we need to differentiate why auto-correlation algorithm is not used in most of the cases.

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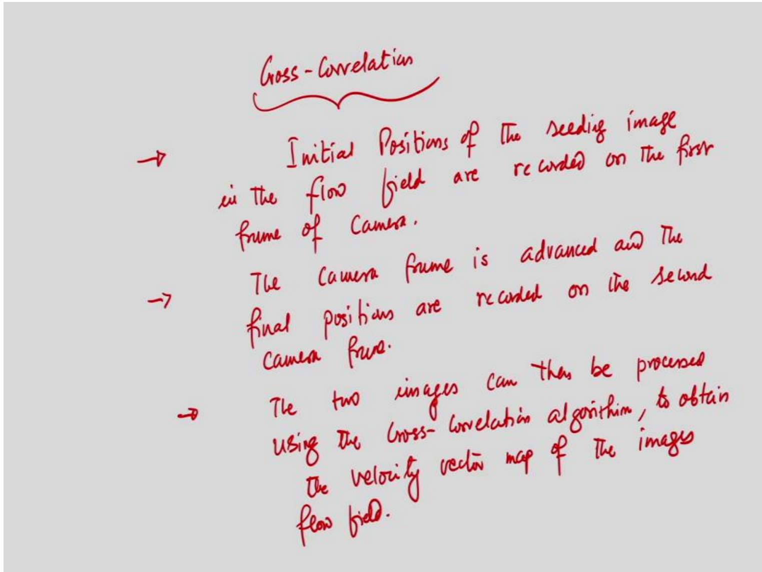

So, now, we will try to discuss about the auto-correlation algorithm. So, you know that we have understood, that in the cross-correlation algorithm, so, if I try to write, to rather cross correlation algorithm, so, if you try to write, we have discussed, we can write a few important points for this technique. And from there, we will try to compare what are the different issues which are not there in the auto-correlation algorithm and that is why auto-correlation algorithm is not used in most of the cases.

So, this cross-correlation algorithm initial position of the seeding image in the flow field are recorded on the first frame of camera, then camera frame is advanced and the final positions are recorded on the second camera frame. Then the two images can then be processed using the cross-correlation algorithm, to obtain the velocity vector map of the image flow field.

So, you have, this is what is the principle of the cross-correlation, I mean method of PIV. So, what is done in PIV, we initial position of the seeding image in the flow field, initial position, positions of the seeding image in the flow field are recorded on the first frame of the camera. Camera frame is now advanced and the final position are recorded on the second camera frame.

And then the two images can then be processed using the cross-correlation algorithm essentially to obtain the vector map of the image flow field and the cross-correlation algorithm. That is what we have discussed here that, when you are capturing two sequential image maps are sub sampled.

So, what we are doing, we are capturing image first frame, camera frame is advanced, we are capturing image in the second frame, but the algorithm is such that when you are sub sampling there will be spatial shift of the, when within this interrogation area, that means, when you are sub sampling you will get the interrogation areas.

So, in a second frame of reference, second frame will get again interrogation areas and there will be an average spatial shift of a seeding particles maybe observed from one sample to its counterpart in the second camera frame, and this is true that flow is present in the illuminated plane, of course, the illuminated plane there will be always flow, so that means seeding particles that we have captured during first phase seems to have a flow, then the particle will now try to move with the flow.

So, the time interval in which we have captured the second image, we can assume that the image seeding particle which we have captured in the first camera frame, there will be a spatial shift of the first in other seeding particle, which are captured in the first frame and that is what I have written, that from the one sample to its counterpart in the second frame that means, the particles seeding particles captured in the first frame will now have spatial shift, and definitely because that there will be a flow.

And the second frame that we are capturing there will get the counterpart that means the first, from the first sample that is a one sample to its counterpart will be there in the second camera image as there is a continuous flow in the illuminating part. So, this is what is done using the PIV analysis. That means, what we essentially, what we essentially measured using this technique that means, we measured the seeding particle, we take image of the seeding particle in a given frame.

Since, there is a continuous flow, particle will move, particle will have spatial shift and again we are capturing the second frame. We are assuming according to the cross-correlation algorithm, that the seeding particles that we have captured in the first frame will also be there in the second frame and that is what the cross-correlation algorithm is.

Now, we will discuss again I am telling that I will be discussing this part again in a greater detail in the context of micro PIV analysis, but at least, this is what is done, that means, if we have identified, if you have marked a few seeding particle in the first camera frame and if we can, if we assume that the first frame that is very important.

That there will be spatial shift may be observed from that, from one sample to its counterpart into the second image that means when we have captured the seeding particle in the first frame, we have different interrogation windows and the samples we have interrogation area samples, there will be a spatial shift because of the flow and the seeding particle, those are there in the first frame of the image.

So, image interrogation area samples, the seeding particle will have spatial shift and this spatial shift may be observed in the counterpart in the second frame. So, we can at least observe that the similar part that those particles have taken this much amount of time to move this much amount of distance, from there we can correlate the velocity of the particle and if we can correlate the velocity of the particle from there we can predict what will be the velocity of the flow. So, this is, what is the cross-correlation algorithm.

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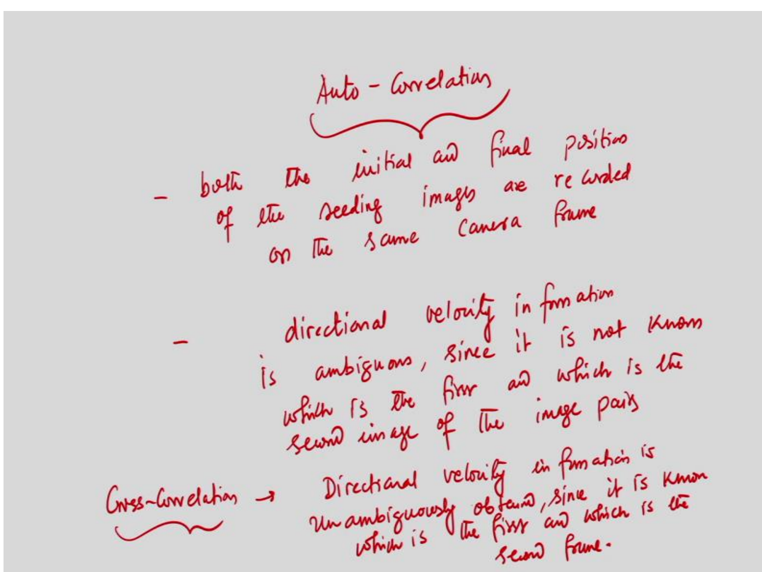

Now, if we try to compare this cross-correlation algorithm with the auto-correlation algorithm. So, what is auto-correlation? Auto-correlation algorithm is that so what we, what we have understood, we have understood that, there will be two different images, the first frame and the second frame. So, in the-auto-correlation both the initial and final position of the seeding images are recorded on the same camera frame.

That means, from this statement, it is clear that, so we are capturing initial as well as final position of the seeding images on the same camera frame. So, if we capture on the, if we capture the seeding images on the same camera frame, it is very difficult to identify, it is very difficult to work, which is first and which is the second. So, there will be always directional velocity always, there will be always a directional velocity so the directional velocity information is ambiguous.

So, the directional velocity information is ambiguous. Since it is not known, which is the first and which is the second image of the image pairs. That means, since we are capturing on the same frame, we cannot identify which is the first and which is the second image and because of which we will have ambiguity in the directional velocity information.

So that means, the directional velocity information is always ambiguous since it is really not known, which is the first and which is the second image of the image pairs that means, you have captured two different images that is true, but we have captured on the same frame. So, it is very difficult to identify which is the first and which is the second. If it is not possible to identify which is the first and which is the second image, then we will have directional velocity ambiguity.

But, if we try to recall for the cross-correlation algorithm, directional velocity information is, directional velocity information is unambiguously obtained, since it is known which is the first and which is this second frame, and that is why the cross-correlation algorithm produces more robust velocity result than the auto-correlation algorithm for the low density seeding case, that means, if the seeding, I mean when you are seeding particle in the flow field, the seeding density is important.

So, if we consider low density seeding, in that case cross-correlation algorithm will provide the robust velocity information as compared to the auto-correlation algorithm. So, that is what is very important to understand. So, now, we will try to discuss what we have understood from this analysis, that is the PIV.

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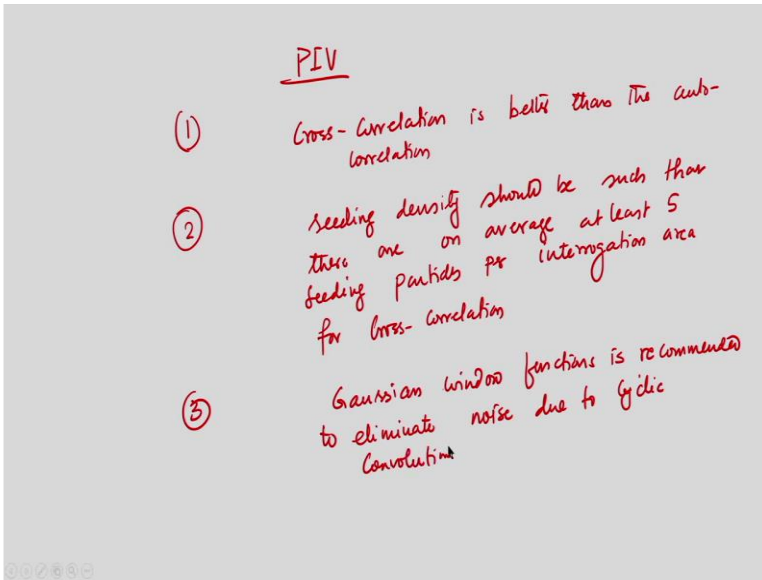

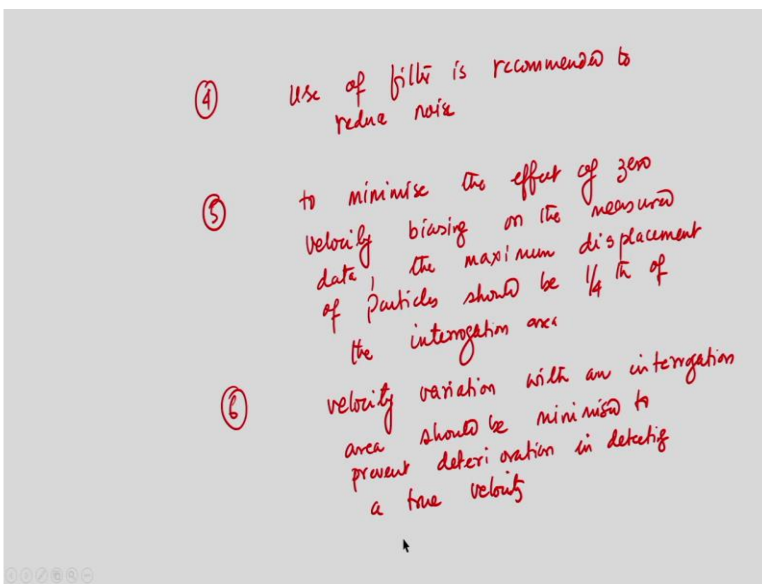

What is that? So, we have understood that a light source is used to illuminate a particular zone in the flow field and the flow, that fluid is, particles are seeded to the flow so when you are illuminating the zone in the flow field, we are illuminating these seeding particles and then we are capturing the image using CCD camera in two different or in two consecutive frame and the captured images are now used for, use to predict the velocity of the flow using cross-correlation algorithm and that is what we have discussed.

So, for this, I mean we have seen that to speed up the correlation the FFT is used. So, I would like to mention a few important point in the context of this measurement technique and in fact, I will try to write all those points. So, what are those points? The use, sorry use. So, cross-correlation algorithm I can write, is I mean better than the auto-correlation, number two, seeding density should be such that there are on average at least five seeding particles per interrogation area for cross-correlation.

Number three, Gaussian window function recommended to eliminate noise due to cyclic convolution. Then number four, use of filter is recommended to reduce noise. Number five, that to minimize the effect of zero velocity biasing on the measured data, the maximum displacement of particles should be one fourth of the interrogation area. Number six is velocity variation within an interrogation area should be minimized to prevent deterioration in detecting a true velocity.

So these six points are important, at least in the context of FFT analysis for PIV. So, in the context of FFT processing, for PIV analysis, these six points are very important. And again, I am telling, I will be discussing the cross-correlation algorithm and also the measurement, I mean the statistical analysis, associated with this technique in a greater detail when I will be discussing about the micro PIV analysis.

Now, finally, if you try to recall one important point in the context of this technique is that, we are using light source that is true, we are illuminating a particular zone in the flow field using a laser light and using the laser light we are trying to obtain, we are capturing two different images and from there we are trying to correlate the displacement of particles which are seeded to the flow and we, know what is the time between two consecutive images captured by the camera from there we can predict we will predict the velocity of the fluid.

So, in this analysis, the seeding particles play an important role. So, when the particles are seeded to the flow, it is assumed that the particles will largely follow the bulk flow, and on the top of that, the particles should have a few important I can say characteristics and before selecting the particle for the micro PIV analysis, these points should be considered. So, if we try to recall in the PIV analysis, we are measuring the velocity of the particle and by measuring the velocity of the particle, we are trying to predict the velocity of the flow, provided the particles are largely following the bulk flow.

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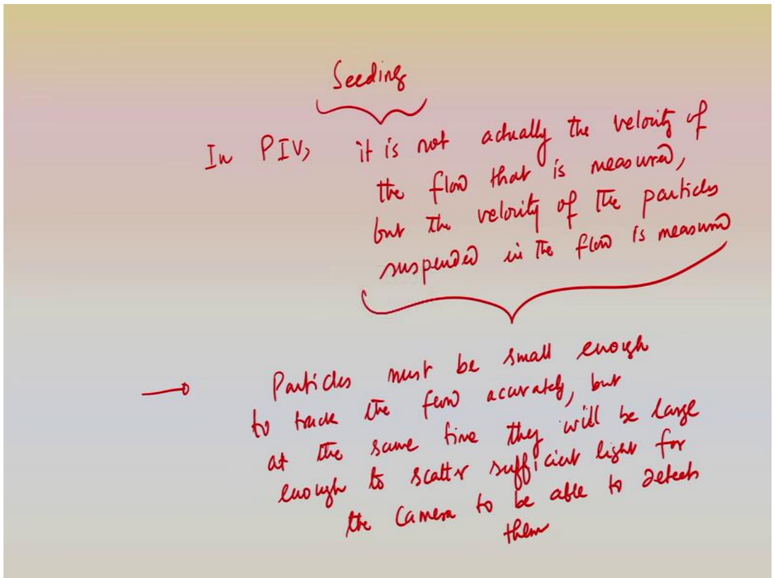

So, the seeding particles and the seeding effect is another important part of this analysis. So, what I said, in PIV analysis it is not actually the velocity of the flow that is measured, but the velocity of the particle that is measured. So, in PIV, it is not actually the velocity of the flow that is measured, but velocity of the particles suspended in the flow is measured and as if the particles are acting like the probe.

So, we are measuring the velocity of the particles and the particles are acting like probe and by measuring the velocity of a particle, we are trying to, we are, we are trying to predict the velocity of the flow. So, since particles are, since we are measuring the velocity of the particles, so the seeding particles will have an important role to play. That means, what are the roles?

There are two important points, I should, I would like to discuss in this context that particles which are chosen for this analysis should have a few important, I can say characters, those who would like to discuss, on the top of that, the size of the particle also will play an important role. So, the particles must be small enough to track the flow accurately, but at the same time, they will be large enough to scatter light for the camera, to be able to detect them, that means particles only a very small, very small particle, neutrally buoyant particle there should not be huge density difference.

So, density of the particles will be equal to, more or less, will be equal to the density of the fluid, neutrally buoyant particles, they will try to largely follow the, follow the bulk flow, but at the same time, the size should be sufficiently large such that they will scatter light which is important for the camera to detect them. So, this is an important point, should be mentioned in this context.

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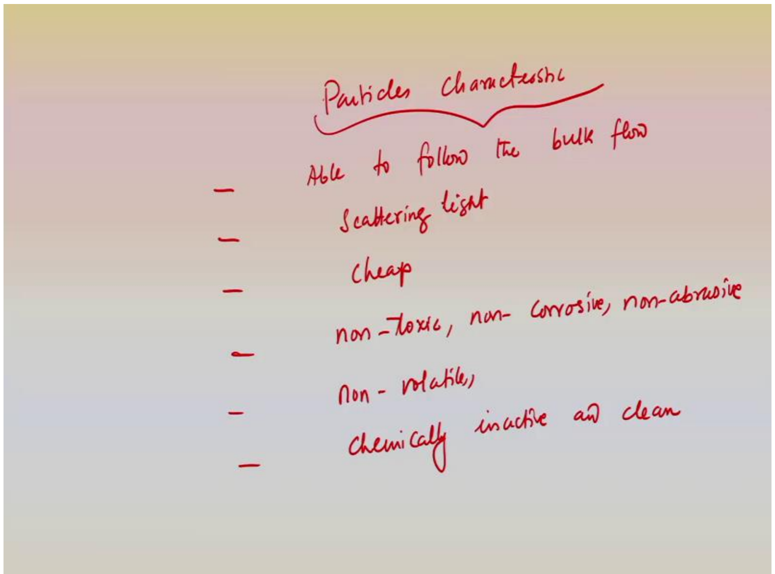

Finally, I would like to discuss, I would like to write, the particles, particles characteristic that means, as I said density of the particles will be more or less equal to the density of the fluid that means, they will have, they will be able to follow the bulk flow, then, I mean, they will be able to scatter light or scattering light, cheap, then non-toxic, non-corrosive, non-abrasive, non-volatile, chemically inactive and clean.

So, these are the few important, I can say features of the particle which should be selected for this analysis, that means the density difference should not be there, they will follow the bulk flow, they will be able to scattered light effectively. Of course the particles are not, particles should not be very costly, the cost of the particle should not be very high, cheap, readily available, non-toxic, non-corrosive non-abrasive, these are the important points non-volatile and the particles will be, particles which are seeded to the flow, should be chemical inactive and the clean. So, these are the important points.

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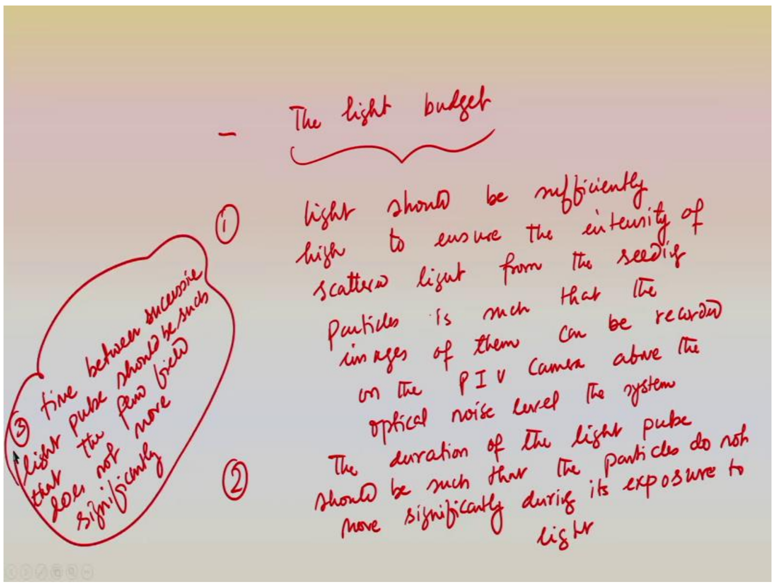

So, now before I would like to conclude, so, in the PIV system, another important part is the lighting system. So, if we try to conclude the light source, which is used to supply light into the area of our interest in the flow field. So, the light, which is supplied, the light budget, light budget that is light which is supplied either using the laser source or from any other source, it should have again a few important.

I can say features that is, number one, the light should be sufficiently high to ensure intensity of scattered light from the seeding particles, to ensure that the intensity of the scattered light for a seeding particles, seeding particles, is such that, the images of them can be recorded on the PIV camera, above the optical noise level, optical noise level of the system.

And number two, the duration of the light pulse should be such that the particles do not move significantly during its exposure to light, to light and finally, number three, that is, the time between successive light pulse should be such, that the flow field does not move significantly. So, this is very important point that is what I was discussing.

So, these are the few important points a light budgets should have, that lights should be sufficiently high to ensure, that the intensity of the light from this seeding particles is such that the images of them can be recorded on the PIV above the noise level, optical noise level of the system and the duration of the light pulse should be such that when they are, when the particles, I mean such that, the particles do not move significantly during its exposure to the light.

That means when the, when we are illuminating the particles using light, particles should not move significantly. And finally, that is very important, that the time between successive light pulses two successive light pulses, should be such that, the flow fields should not have significant progress, the flow field should not have significant movement, otherwise, our objectives should not be fulfilled.

If we can, if we try to recall that I was discussing even in today's class that we are capturing the first image that will be stored in the first frame. And we are using the cross-correlation algorithm, we are ensuring that the part of the first, you know, first image that is captured, we can divide into small areas that is interrogation windows, a few of those interrogation windows will be there even in the second phase.

So, that, is what is the correlation. So, the time pulse between two successive, time between two successive pulses should be such that, that the flow field should not have significant movement. So, to summarize today's class, we have discussed about the basics of the cross-correlation algorithm.

We have tried to understand what is essentially done using this algorithm, and using this algorithm, the velocity of the particles are calculated. And as I said, in PIV analysis, we are actually measuring the velocity of the particles, not the velocity of the fluid. By measuring the velocity of the particles we are actually trying to predict the velocity of the fluid or velocity of the flow.

Accordingly, we have discussed the seeding particles should have a few important characteristics and finally, the light which is very important component of the PIV system should have also a few important points and we have tried to understand all those points. So, with this, I stop my discussion today and we will continue our discussion in the next class. Thank you.