

Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer

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Week – 07

Lecture - 34

Particle Image Velocimetry – 4

All right, so in this particular part of the PIV lecture, we are going to talk about perspective projection. Now, as you know, in most cases, the particle that is there in the flow field, for example, if this is the flow field and if this is the laser sheet illuminating the flow field or part of the flow field, the particle may not just move in the plane of the light sheet. So this light sheet has a finite thickness. So the particle may not actually move in the plane of this light sheet, but it may actually have a velocity component that is perpendicular to the light sheet. That means it might have a Z-component, for example. So, in order to fully explain the influence of the velocity components perpendicular to the light sheet, the location of the image points in the coordinate system x , y , and z —okay, xyz —that the lens actually images needs to be taken into consideration, because this is what the lens is actually imaging.

Perspective Projection

In most cases the particle in the flow will not just move in a plane parallel to the light sheet, but will also have a velocity component perpendicular to the light sheet plane. In order to fully explain the influence of the velocity component perpendicular to the light sheet on the location of the image points in the coordinate system x, y, z the imaging through the lens must be taken into account.

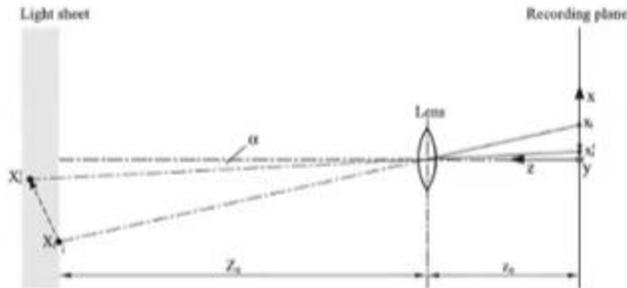
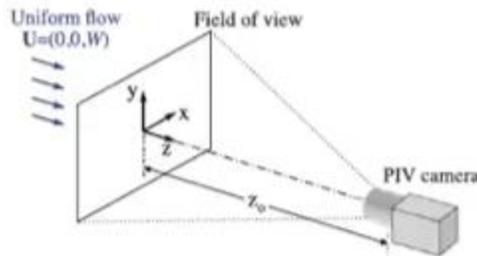


Fig. 2.60 Imaging of a particle within the light sheet on the recording plane

D defines the particle displacement between the two light pulses by its components DX, DY, DZ in the object plane (light sheet). The following relation between the location of corresponding images in the image plane (sensor) due to the recording of a particle at position x_i and x_i' is obtained



This is the imaging of a particle within the light sheet in the recording plane. So if D defines the particle displacement, for example, between two light pulses, then the components of D will be $dx, dy,$ and dz . There will be three components. Okay, so in other words, we will see in the next one that the relationship between the location of the corresponding images in the image sensor plane, due to the recording of a particle at X equal to X_i and X equal to X_i' , is actually a little different.

As you can see, this is what the image of the particle actually looks like in the imaging plane, where D denotes the displacement. You'll see in the next slide what it exactly means. So this is your camera, this is your field of view, and this is the distance of the object from the PIV camera. All right, and this is what we are actually recording, so this is what happens. If you look at $\tan \alpha$, it is x_i'/z_0 .

Okay, which you can see over here, this Z_0 is basically this small z_0 . Okay, so this is the angle that it actually makes, is that okay? This is the angle from the axis and the optical axis. So the image displacement, which is d , $x'_i - x_i$, corresponds to a certain particle displacement, okay? So what it looks like is that the image displacement is actually this, okay? $x_i - x'_i$, okay? And corresponding to a certain particle displacement, which is actually D , this is the image displacement that we see, okay? The image displacement corresponds to the particle displacement that we see over here. Remember the x_i ; the x corresponds to the image. Where the X corresponds to the object.

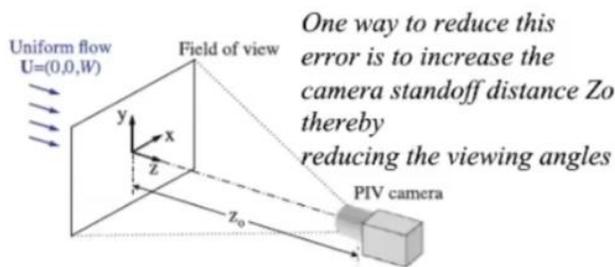
$$\tan(\alpha) = \frac{x'_i}{z_0} \quad (2.25)$$

The image displacement $d = x'_i - x_i$ corresponding to a certain particle displacement D can be obtained:

$$x'_i - x_i = -M(D_X + D_Z x'_i / z_0) \quad (2.26)$$

$$y'_i - y_i = -M(D_Y + D_Z y'_i / z_0) \quad (2.27)$$

- It can be seen in Eqs. (2.26) and (2.27), that a particle displacement in the Z -direction influences the particle image displacement, especially for large magnitudes of X_i and Y_i at the edges of the observation field
- This effect introduces an uncertainty in measuring the in-plane velocity components, because it cannot be separated from the in-plane components. This uncertainty will turn into a systematic error if it is assumed that PIV determines just the in-plane components even for larger viewing angles



So you can understand that this displacement that you are measuring, $x_i - x'_i$, actually corresponds to some particle distance that the particle has traveled in the light sheet. Actually, in the object plane. So, in other words, if your $x_i - x'_i$ is given as, then D is the actual particle displacement. So it is a magnification factor multiplied by these quantities. So you can see there is an X displacement and then there is a Y displacement, both on the image plane.

They correspond to the actual particle displacement modified by the magnification factor

and the out-of-plane particle displacement, which is the component of the particle displacement that is perpendicular to the light sheet. Okay. So it can be seen from these two equations, which are 2.26 and 2.27 from Marcus Raphael's book, that the particle displacement in the Z direction influences the particle image displacement.

So, if the particle moves in the Z direction, what happens? It influences the actual image displacement that occurs in the X and Y plane. Okay. So, especially for large magnitudes of x_i and y_i , the edges of the observation windows are a very, very important factor. So this effect incorporates an uncertainty in measuring the in-plane velocity components because it cannot be separated from them. Because remember, we are using this to calculate the in-plane velocity components, but then you already know the magnification factor.

However, there is no one-to-one correspondence with the displacement in the x direction and the y direction of the actual particle, because then you have this out-of-plane component which actually comes into the picture, which is $(dz \ x'_i)/z_o$. Okay, so this introduces what we call a systemic error. Okay, if we assume that the PIV only measures the in-plane components, it is still valid even for large viewing angles. The larger the viewing angle, the larger this $\tan \alpha$ is; okay, the larger this $\tan \alpha$ is, the more you will have, you know, if this value goes up as a result of that, you will have even, uh.

.. you know, uh... even more systemic error creeping into the system, so uh.

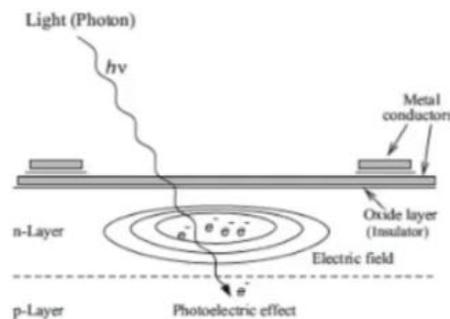
.. One way to reduce this error is to increase the camera standoff distance, z_o , thereby reducing the viewing angle. So one way to do this, to reduce this error, is basically to reduce the camera standoff distance, z_o , and thereby reduce the viewing angle. So your field of view is very, very important because towards the edge, this effect becomes quite substantial. So this is the perspective. Okay, now let us look at the cameras in particular,

what these cameras do and what they are made out of.

Characteristics of CCD Sensors

- In general a CCD is an electronic sensor that can convert light (i.e. photons) into electric charge (i.e. electrons). CCDs, either in the form of a line (e.g. in a line scan camera), or arranged in a rectangular array (of course other specialized forms also exist). The individual CCD element in the sensor is called a pixel. Its size is generally of the order of $10 \times 10 \mu\text{m}^2$, or 100 pixel/mm.
- The operation of these pixel is best described by referring to the schematic cross-section shown in Fig. 2.64. The CCD is built on a semiconducting substrate, typically silicon, with metal conductors on the surface, an insulating oxide layer, an n-layer (anode) and a p-layer (cathode) below that. A small voltage applied between the metal conductors and the p-layer generates an electric field within the semiconductor. A characteristic of a pixel is its fill factor or aperture which is defined as the ratio of its optically sensitive area and its entire area. This value can reach 100% for special, scientific-grade, back-illuminated sensors or may be as low as 15% for complex interline-transfer sensors

Fig. 2.64 Simplified model of a (CCD) pixel



So first and foremost, normally, PIV cameras can be CCD cameras, especially low-speed PIV cameras. So in general, what happens is that a CCD camera actually has an electronic sensor that can convert light into electric charge. In other words, it is the photoelectric effect. The CCDs can come in the form of a line. There are line-scan cameras.

Or it can be arranged in a rectangular array. Okay, so an array of a CCD camera, if you look at it, consists of these small, you know, what we call pixels. Okay, so the individual CCD element is called a pixel. And the pixel is usually 10 microns by 10 microns or 100 pixels per millimeter. So how does it actually work? The CCD is built on a semiconductor substrate.

Typically, it is a silicon substrate with metal conductors on the surface. So, these are the metal conductors on the surface. And then there is an insulating oxide layer just below it. Then a small voltage is applied between the metal conductors and the p-layer. And that actually generates an electric field within the semiconductor.

So, do you understand? So there is a semiconductor that is now covered by an oxide layer and a metal conductor. So once you do this, if you apply a small voltage between the metal conductors and the p-layer, you generate an electric field within the semiconductor. The characteristic of a pixel is also called its fill factor. So we will get to that a little later. So, as light impinges, you basically release electrons.

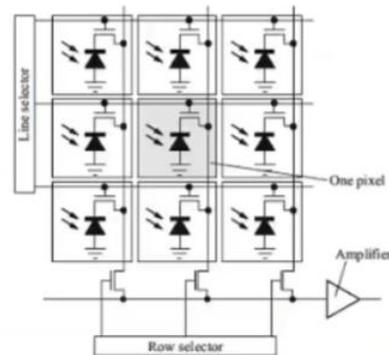
And so basically you have an accumulation of charge, which depends on how much light it is actually gathering. So the characteristics of a pixel are also called its fill factor or aperture, which is basically defined as a ratio of its optically sensitive area to the entire area. We'll see why that is important because you know the optically sensitive area, and then it can have a larger area that is not optically sensitive. Especially the CCD cameras when it has to; it has got blind pixels as well, where it basically shifts between measurements. So the value can reach 100% for special scientific-grade cameras, and it can be as low as 15% for interline sensors.

So, 100% of the camera may actually cover the whole area. So we will see a few of those examples later. Then, of course, we now have the advancement of the CMOS sensors. Now, the main advantage is that each CMOS, unlike the CCD pixels, has photodiodes in the CMOS sensors, and this can be controlled. So the fundamental principle is shown in this figure, which is 2.6. Here, you can see that each individual pixel contains an electronic circuit. So you can see that each pixel is this, and it contains an electronic circuit, okay? So this is called an active pixel. So the active pixel architecture with individual access offers individual access to each pixel, allowing you to integrate fundamental camera functions like amplification, nonlinear signal transformations, and analog to digital conversions on the chip, et cetera. So you can have individual control of these pixels. So these are basically photogates or phototransistors.

Characteristics of CMOS Sensors

- Main advantage compared to other techniques like photogates or phototransistors is their high sensitivity and relatively low noise.
- In contrast to CCD pixel, the photodiodes in CMOS sensors can be controlled separately by MOS-FET transistors.
- The fundamental principle of a CMOS sensor is shown in Fig. 2.65. Each individual pixel contains an electronic circuit. This active pixel architecture together with the individual access to each pixel offer some major advantages and allows to integrate fundamental camera function like amplification, non-linear signal transformations and AD-conversion on chip.

Fig. 2.65 Simplified model of a CMOS sensor



Okay, so if you now look at the spectral characteristics of a camera, it is also important. So similar to photographic film, the digital sensor also has sensitivity and a spectral response. So, the pixel sensitivity is also called the quantum efficiency of the camera. It is defined as the ratio of the number of generated and collected photoelectrons to the number of incident photons. So you can see the number of photons is incident and you generate a certain amount of photoelectrons.

Spectral Characteristics

- Similar to photographic film, the digital sensor has a sensitivity and spectral response. A pixel's sensitivity or quantum efficiency, QE, is defined as the ratio between the number of generated and collected photoelectrons and the number of incident photons per pixel and is most commonly measured in collected charge over light intensity $Cb/(J \cdot \text{cm}^2)$.
- To reduce the susceptibility to infrared light, many commercially available CCD and CMOS cameras come equipped with an infrared filter in front of the sensor.

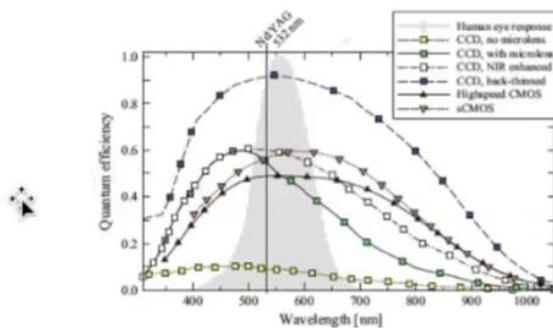
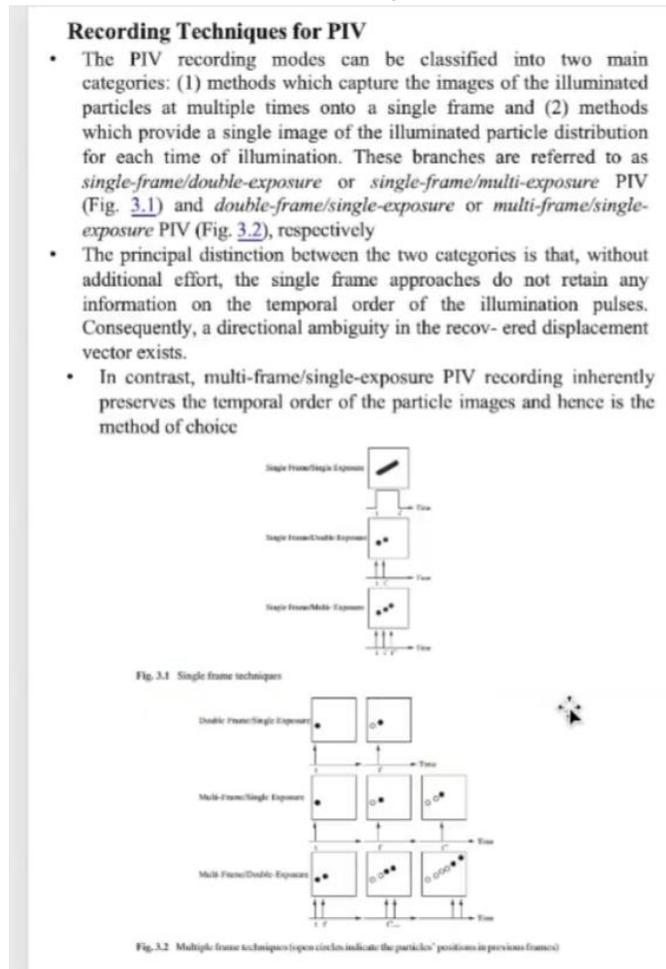


Fig. 2.67 Quantum efficiencies for various CCD and CMOS sensors. The vertical line indicates the wavelength of the most commonly used laser for PIV. Gray shaded area represents the luminous efficiency function of the human eye. Quantum efficiencies obtained from manufacturers' data sheets: Kodak KAI-4020, Sony ICX285AL, e2v CCD201-20, PCO AG Dimax-S4, Andor neo sCMOS

So, what is this ratio? The more the number of photoelectrons that are released, the better the quantum efficiency of the camera. Okay, so if you can see, this is quantum efficiency with wavelength. You can see that these are different CCD cameras. Okay, forget about what they are; I mean, there is a CCD with microlens, with NIR enhanced, and a lot of things back-thinned. Okay, so you can all see that at around 532 nanometers, where an Nd:YAG laser actually operates, the cameras have their peak quantum efficiency.

Remember, the quantum efficiency drops on both sides quite rapidly, particularly in the UV. In the UV region, the quantum efficiency is rather low, and so it is in the near IR region. So if you have measurements, if you have radiation that you are collecting at these kinds of wavelengths, then your camera will not be sensitive enough because its quantum efficiency will be rather low; in other words, the number of generated and collected photoelectrons will be low. On the other hand, for PIV, because most of the time we use an NDAG laser, which is 532 nanometers, this is the best case, so you can use the maximum quantum efficiency range of the camera to do this. So in order to reduce susceptibility to infrared light, many cameras come equipped with an infrared filter so that they cut off the light that is beyond a certain wavelength.

So that is also done in those cases. So how does a PIV recording actually happen? So, As you know, the PIV recordings now can be classified into two categories. One is that you can capture the particles multiple times in a single frame. So if you look at this figure over here, you can see that this is a single camera exposure, single frame, single exposure. You can see that if you keep the exposure time too long, this particle will become like a streak. Okay, so this is the camera's opening and closing time.



Okay, so T and T' . Okay, on the other hand, if you have a single-frame multi-exposure camera, that means the camera is still a single frame, but it has multiple exposures. Okay, so you can get, uh, you know.

.. Or a double exposure. So the camera is actually exposed for two selected times, T_z and T' . You will see these two particles. When you take the same image, you will see the particles actually moving. All right, you can also do what we call a double-frame single exposure, okay? So in this case, you know, the principal distinction is that the single frame approaches do not retain any information on the temporal order. So there is a directional bias or a directional ambiguity in the recovered displacement vector.

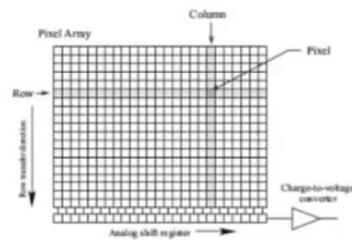
In contrast, when you do multi-frame single exposure, the PIV recording preserves the temporal order. You can also do it in double frame mode, okay? Double frame single exposure mode, okay? Or you can do double frames. This is double frame single exposure, this is multi-frame single exposure, and this is multi-frame double exposure, so you can do all these kinds of things using the current cameras that we have. Okay, so let's look at the digital cameras. So in this section, we describe the CCD and CMOS-based cameras, which we have already covered a little bit.

And we are also talking about flash lamp pumped double oscillator Nd:YAG lasers, which provide high pulse energies. and it has a rep rate that matches the framing rate of the cameras. Typically 10 hertz, the cameras can also go up to 10 hertz. You can go to high-speed lasers; your camera can also be very high-speed these days, especially the S-CMOS cameras. Okay, so the CCD cameras that are used for PIV have two important advantages.

Digital Cameras for PIV

- The following section describes CCD and CMOS based digital camera which over the past decades have become the work horses for nearly all technical and scientific PIV applications that required only moderate or no temporal resolution.
- Flash lamp pumped double oscillator Nd:YAG-lasers offer high pulse energies and repetition rates that matched with the frame rates of most of the commercially available CCD cameras.
- The CCD cameras used for PIV offer two important advantages, one being increased spatial resolution, the second the electronic architecture that permits two PIV recordings, temporally spaced by microseconds or even nanoseconds, to be recorded by the same camera

Fig. 3.3 Typical CCD sensor geometry



- It should be pointed out that, in contrast to most CMOS sensors, the array has to be read out sequentially in a two-step process: after exposing the sensor the accumulated charge (i.e. electrons) is shifted vertically, one row at a time, into a masked (optically blind) analog shift register on the lower edge of the sensor's active area.
- Each row in the analog shift register is then clocked, pixel-by-pixel, through a charge-to-voltage converter and thereby provides one voltage for each pixel.
- Depending on the employed image transmission format the read-out of the sensor can either be sequential (also known as *progressive scan*) or interlaced, in which first all odd rows are read out before the even rows are accessed.

One reason is that they have increased spatial resolution. The second is that the electronic architecture permits two PIV recordings because you have to obtain two frames. Okay, and these can be separated by microseconds or even nanoseconds, and they can be recorded by the same camera. The same camera can take two images or two

frames that are separated by microseconds or even nanoseconds, and you can record them on the same camera. So those are the advantages because you need two frames.

So it should be noted that, in contrast to most CMOS sensors, what happens here, let me try to see, is that this is the pixel array of a CCD camera. What you see at the bottom is basically called an analog shift register. So what happens is that, in contrast to CMOS sensors, each array is read out sequentially in a two-step process. So after the sensor is exposed and collects a certain amount of accumulated charge, which is basically the photoelectrons, these electrons are shifted vertically one row at a time.

Vertically, one row at a time. Into a masked area, this is the part where it is masked, and it is an optically blind analog shift register on the lower edge of the sensor. And each row is then clocked, pixel by pixel, using a charge-to-voltage converter, thereby providing a voltage for each pixel. So depending on this image transmission format, the readout of the sensor can be sequential, which is called progressive scan, or interlaced, in which first all odd rows are read out before the even rows are attempted. So you can see these charges are now shifted to an analog register from which they are basically read out using a charge-to-voltage converter.

So this is how the principle actually works. And depending on the employed image transmission format, the readout of the sensor can be either sequential or interlaced. So if you look at this as the standard CCD, this is like a frame transfer CCD, this is an interline CCD, and this is a full frame interline transfer CCD. So you can see that this is what it says: these are the pulses. These are the laser light pulses and how the camera is actually open between the two pulses. So you have a frame transfer CCD; this is where it is open, and this is the period during which the charge transfer actually happens.

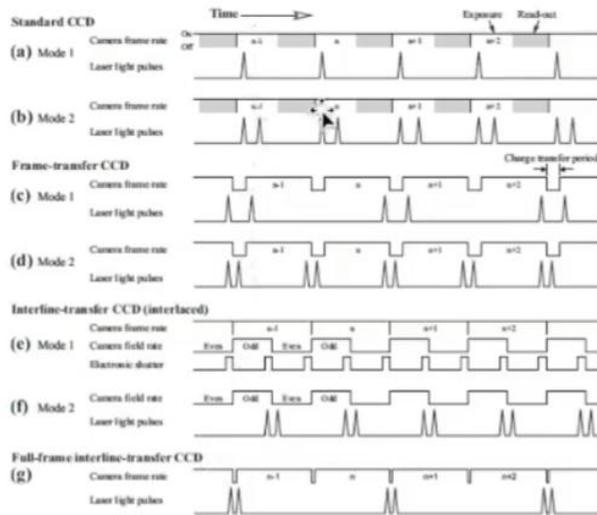
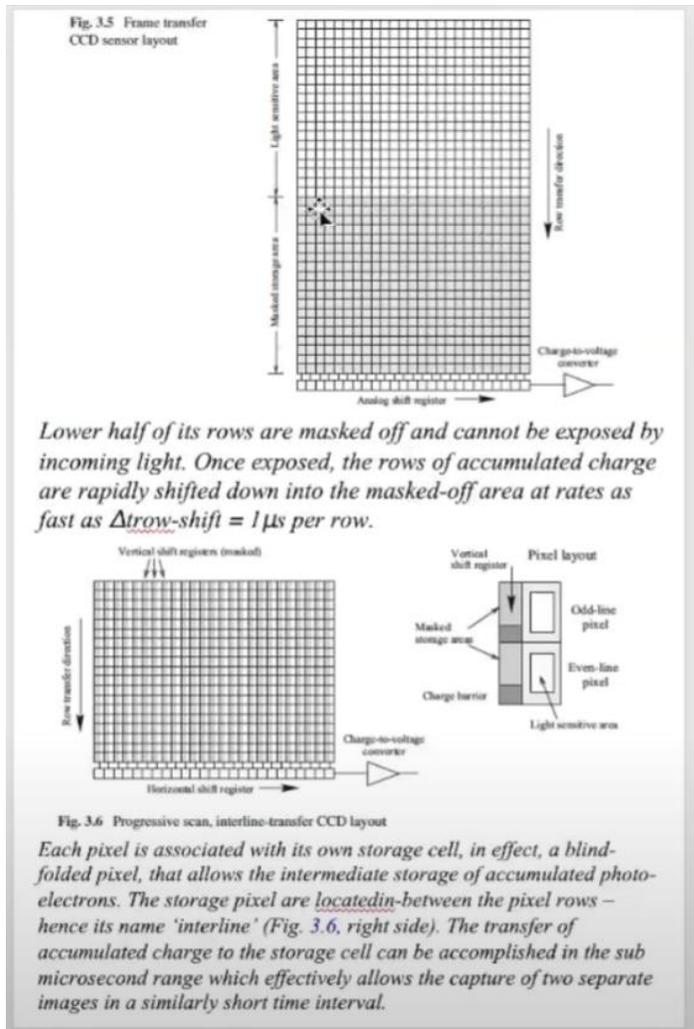


Fig. 3.4 Timing diagrams for PIV recording based on various types of CCD sensors

The timing charts given in Fig. 3.4a, b summarize how the particle illumination pulses have to be placed to produce single exposed or multiple exposed PIV images.

Okay, so this is the period. So you can see that these are the timing diagrams, okay, that show how particle illumination charges have to be produced to, you know, see what is going on. So when it's interlined, this is even, and this is how this is actually read out, all right? So you can see that in the case of frame transfer mode, what happens is that the lower half of the rows is all masked off and cannot be exposed to the incoming light. So once exposed, the rows of the accumulated charge, which are this one, transfer the charges rapidly downwards into this masked-off region. With about one microsecond per row. And then that is converted to an analog charge-to-voltage register, and this becomes accessible for the next image.



So in the case of an interline transfer, what happens is that if you look at it very carefully, you will see that each pixel has its own storage cell. Okay, so each pixel has its own light-sensitive area, and this is the vertical register. So that means there are blind pixels that allow immediate transfer and immediate storage of the accumulated photoelectrons. So, as soon as this is exposed, it kind of stores in this vertical shift register. The storage pixels are then located between the pixel rows; hence, the name interline.

So there will be another light-sensitive pixel after this, and then again a vertical shift register to its left. The transfer of accumulated charge to the storage cell can be accomplished in the sub-microsecond range, which effectively allows for the capture of two separate images in a very short time interval. So you understand, this is where the photoelectrons accumulate. They are quickly transferred from here to there.

From here to there. The vertical shift register, right? And then they are taken out. So you have alternate rows and alternate columns here, which are basically not photosensitive.

They are masked off, okay? Blindfolded pixel, as we call it, all right? So, that is how this transfer mechanism actually happens, okay? And the CMOS camera, we have already covered how that actually works. So typically, just to go back, look at this diagram properly because this is what you need when you actually do your PIV measurement. You need to synchronize your camera and laser properly, and you should also know how fast the charge transfer actually happens, as that determines the time frame between the two pulses.

This also allows you that the shorter the time distance or the time interval between the two pulses, the higher the velocity that you can actually calculate or measure. So that is one area in which you have to look at different transfer techniques, like frame transfer and interline CCD transfer, that we talked about just now. And this is a mixture of the two: the full-frame interline CCD transfer. We have already talked about the mechanisms, how the charges are actually transferred, and how it is possible to take the second image. And we also talked about what a single exposure, double exposure, and stuff like that is, okay? And please pay attention to these kinds of figures because this is how that thing happens.

And CCD cameras and CMOS cameras, we have already done quite a bit of work on the CMOS cameras. We have explained that, basically, if I go back, it is this: each camera has its own electronic circuit, which allows us to do this, but it also suffers from noise issues and low quantum efficiency.

Remember what quantum efficiency was? We kind of, uh... you know, showed this here, so you can see the quantum efficiency of scientific CMOS cameras is improving. Okay, in that particular category, but normally you will see that there are CCT back thin CCTs which can have much higher quantum efficiency, and you can collect, therefore, more light. Your image intensity becomes huge; you can have higher viewing angles. In that particular case, your zone of illumination will be brighter. Also, remember one thing: that the The out-of-plane component of the displacement is actually embedded in your image displacement.

As a result, this leads to what we call highly systemic errors. Now, in this next class onward, we are going to cover the mathematical background of statistical PIV evaluation. So far we have talked about how to take the image, how to create the laser sheet, and what the caveats are. Now we are going to look at how, if we take the images, we can process them and how the PIV recordings, as we know, are already subdivided into interrogation areas and how these interrogation areas can finally be used to calculate the velocity. So the first mathematical description of statistical particle image velocimetry was given by Ron Adrian. In this early work from 1988, he used autocorrelation methods,

and later it was expanded to cross-correlation.

A careful and complete mathematical description was given by Westerwill. And, uh, you know, Adrian and Wester published the most comprehensive book on particle image velocimetry about 13 years ago. Okay, so this is a practical handbook. If you want to know more about particle image velocimetry per se, you have to go through those kinds of books. Okay? So in the next lecture, what we are going to do is start looking at the particle image locations and then try to see how those image locations can be used and how the interrogation windows can be used to calculate the image intensity and then take it forward for the velocity calculations.

So we will stop here, and please go through this lecture properly. We have covered a lot, from perspective projection to the sensors that are used, to the definition of quantum efficiency, how that charge transfer actually happens, and what the different modes of charge transfer are, especially the interline and the full frame transfer. So you should look into all of these things before you move on to the next one.