Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer
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Week – 05
Lecture - 24
Schlieren and Shadowgraphy – 2

 All right, so in this particular talk, remember that we already did a classification of the optical methods where it was density-based and when there is a deflection of a light ray involved. He said that either you can use shadowgraphy and Schlieren, or we can. So shadowgraphy depends on the second derivative of the density, whereas Schlieren depends on the first derivative. And interferometry depends on absolute density. So let's take a look at the shadowgraphy setup. So in this case, if you look at it carefully, you just need a light source, a point light source, a Schlieren object right here, which is a Schlieren Rate, and a screen on which the shadow is basically cast.

 So these are the three components that you exactly need for doing your measurements. Alright, if you look at it carefully now, the point light source emits the light and there is this Schlieren object. What it does is that as the light passes through this medium or this area of interest, it undergoes a slight deviation because of the density change. And we already talked about it; if you go back, you will see that these are the deflections that we already calculated or showed you how to calculate.

 There is a deflection of some sort. As you can see, without the Schlieren, this would have gone there. But now it is deflected and has moved a little bit upward on the screen. So, because of this effect, you have a certain deflection, which is ε, so this region over

here actually receives more light compared to this particular region originally. All right, now, if you do this, this does not involve any mirror or any lens or anything like that.

Now, if you have an object, like, for example, a bubble or something like that, a dense... Dense gas bubbles, say for example, and then you again have a point light source, and then you have a lens over here. This lens basically collimates it and makes it up like a pipe, a type of light, basically a pipe flow type of light.

Okay, so now it encounters this sphere. What happens is that again, without the sphere, these rays would have gone to these places. Now they are deflected a little bit because these rays are deflected. There are regions that have extra illumination and then there are regions that have less illumination, as you can see. So this is the shadow that is actually cast on the screen, so you can see this is basically the bubble.

This uses a lens, for example, to make the light beams parallel, and they impinge on this particular object. Now, if you look at the distance, this is again the line of sight. So if you see that this is where the screen is placed, So the reduction or change in illumination with respect to the overall illumination is given by this path length, which is L, which we already saw. And this is the second derivative of the logarithm of the refractive index. And this is integrated over the Z.

So this is how this entire thing, this variation of intensity or the illumination deficit, as we can call it, is basically fast. Now for weak refraction, when we apply the Gladstone-Dale formula, it reveals that when you are dealing with shadowgraphy, this has a dependence on the second partial derivatives of the density. Or in other ways of telling, this is that shadowgraphy responds to rapid changes in the density gradient. So this is very useful when you are actually dealing with shocks, for example. When you are dealing with shocks and things like that, there is a rapid variation of the density gradient itself.

So it is not just the variation of density, but it is the variation of the density gradient; in objects like shocks and things like that, the density gradient varies quite a bit. As a result of that, you should know that the shadow graphic actually depends on that. So this is the thing. So when we say in a shadow graph the second-order derivative, it refers to the fact that this optical technique is most sensitive to the changes in the second derivative of the fluid density. It means that it primarily visualizes those areas where the curvature, or basically the slopes of the density variations, are significant rather than just changes in density itself.

So this is the main thing. So it is particularly effective at detecting very sharp changes in

density, like those in shock waves, because it is sensitive to the second gradient. So it is, as you know, used to visualize shock waves, Prandtl-Meyer expansions, and other phenomena where there are significant density gradients. So it is very useful when the density gradient is sharp. So that the second-order derivative of the density gradient is present, but it's quite high, so to speak.

So that is the thing that we are kind of, you know, this arc; shadowgraphy, therefore, becomes a very useful technique. But as we can see, it is just that if you look at this particular formula, the second derivative comes into the picture, and this is just an intensity variation. And why does that variation happen? Because of the Schlieren object, some parts that are supposed to receive illumination receive less illumination, and some parts receive more illumination. So, basically, you create a contrast. Contrast is actually created because of this.

All right. So this is quite interesting. And I think this is the way this discussion is actually moving forward. And so, as we know that since it is sensitive to the second partial derivatives of density, and because density and refractive index are linearly related, we can utilize this for changes and use the change in refractive index to detect certain phenomena. For example, here is a bubble. This one actually shows a shock.

This is from VT, Virginia Tech's gallery. So you can see that there is an object and a detached shock. This is called a bow shock. Because it's a blunt body, the shock is actually detached. So you can clearly see the shock front.

And then you can see the very fine-scale structure of the flow behind this fluffy body. So you can see this has pretty fine structures of different length scales. And time scales, this is particularly important because you know these are the structures that actually designate turbulence in a way. Okay, so the flow behind this normal portion of the shock is subsonic, but then this flow gets accelerated as it moves along this bluff body.

Examples: Shadowgraph of blunt body in supersonic flow

APPLICATION: DETACHED SHOCK WAVE
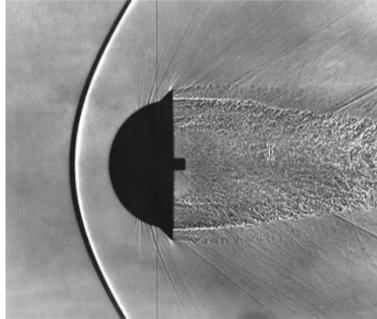
The shadowgraph of a supersonic flow around a finned hemisphere

The bow shock is detached Because of the blunt body.

The flow behind the nearly normal portion of the shock is subsonic. Thus, no Mach waves are seen near the line of symmetry.

As the subsonic flow sweeps over the body, it accelerates, ultimately becomes sonic and then supersonic.

The position of the transition to supersonic flow can be estimated by noting the position of the first appearance of Mach lines on the body.

Data from http://www.eng.vt.edu/fluids/msc/gallery/shocks/

And you know, so. Because it is subsonic, there are no Mach waves that are seen near the line of symmetry. But as you move towards the aft of this particular object, you can actually see the flow accelerate, ultimately become sonic, and then become supersonic. So you can see the Mach waves and the Mach lines. On the body, you can see a very fine scale structure behind the bluff body. So this is a very typical example where a shadow graph has been used to detect very fine-scale structures within this particular flow field.

Examples: Shadowgraph of Supersonic Bullet

APPLICATION: A .308 CALIBER BULLET

Shadowgraph of Winchester .308 caliber bullet traveling at about 2800 ft/sec, M=2.5.

Curvature of the Mach lines generated at the nose

Data from http://www.eng.vt.edu/fluids/msc/gallery/shocks/
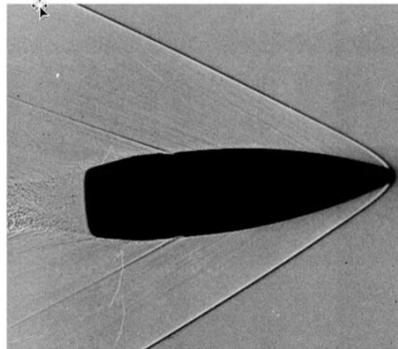
As I said, because the density gradient here is very sharp, the variation of the density gradient is also quite large. The result of that shadow graph can pick up this kind of stuff quite easily. Then, of course, if you have a second example in which you actually have an attached shock now, this is also from VT, Virginia Tech. So here also you can see the

shock and then you can see the very fine scale structure behind the bullet.

This is a .038 caliber bullet. So this is the bullet. And then you can see the very sharp contrast that you actually receive. So the curvature of the mark lines is generated at the nose. You can see a lot of fluid mechanics information you can get just by looking at the structures that are created by these flow fields.

And you can see very fine scale to very sharp structures as well because, again, of the sensitivity with respect to the density gradient. Okay, so this is fantastic. I think this is one way in which you can see that there are many things that can be done. You can also do something called retroreflective shadowgraphy. So this particular image that you see on this one and this one is from NAL, from Dr.

L. Venkat Krishnan's work and the work of his colleagues. So this is particular: this retroreflective shadow graph. Um, it's particularly useful when you are dealing with very high-speed flow applications because you need to have a lot of fidelity with respect to the speed. That means you can acquire data at a very high speed, so your image intensity, um, or The light intensity needs to be substantial.
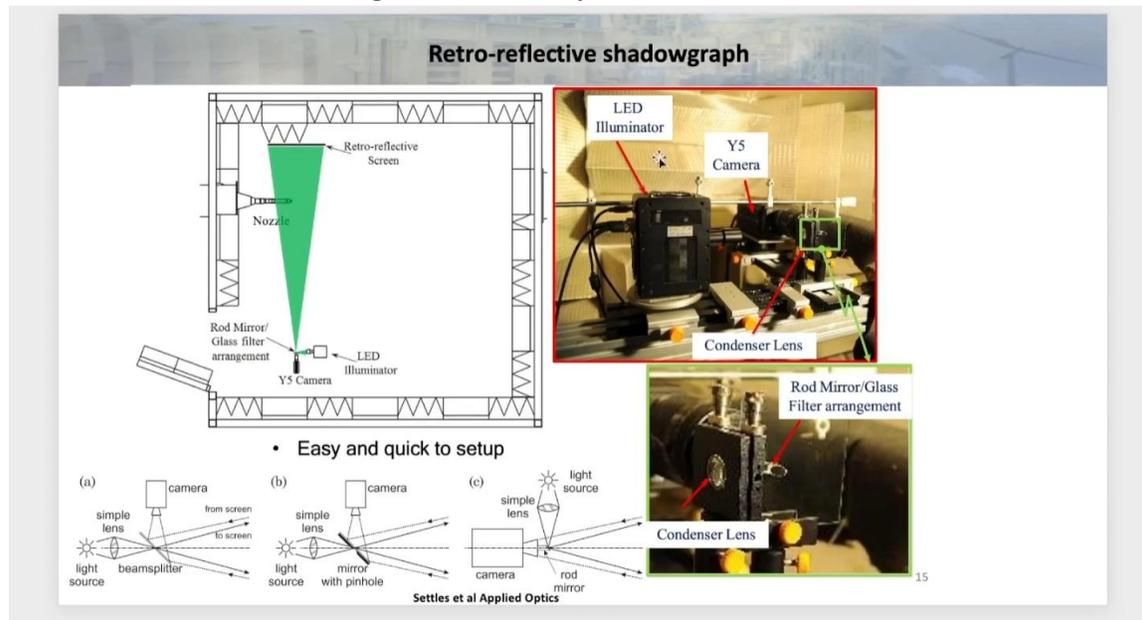
Otherwise, you cannot do this. So as a result of that, this retroreflective shadow graph comes into the picture. You can also read Settle's paper on applied optics. What it does is very simple. Let us look at this particular thing. So there is a camera that is equipped with a lens.

And then there is a rod mirror, which is cut at a 45^0 angle. So you can see some kind of mirror like this. So the light source, whatever it is, you use a simple lens to focus it on the mirror on this side, and then the light basically goes through the object of interest, which

in this case is a nozzle with a supersonic flow, and then there is a retro-reflective screen that lies on the other side that is highly reflective, so whatever intensity of radiation falls on it basically returns all of that. That reflected light then comes back; it goes through the same collector optics and then goes into the camera. I think this is how this actually works.

There can be variations of this, so for example, here you use a beam splitter. Once again, the camera is somewhere here. What happens is that this is a light source; you use a lens to focus on the beam splitter. And then you split it on the screen. That means the retroreflective screen that you see over there.

And the object, the Schlieren object, lies somewhere there. And then the reflective screen returns most of the things to this particular back. Then you use the beam splitter to collect them and essentially transfer them to the camera through the normal. So the camera is basically focused here. So this arrangement involves either using a rod, a mirror, a glass filter arrangement, or this kind of beam splitter arrangement.

And this is a retroreflective screen, highly illuminated. So, this light source is usually an LED illuminator. And you have a high-speed camera with a Wi-Fi feature that is used now. Okay, and you know, there are other things also, like for example, you can use a mirror with a pinhole. Once again, it's the same thing; you focus on the pinhole, and then from the pinhole, the rays basically diverge and go to the, uh, so this camera has a hole, basically.

It goes to the screen, and from the screen, it returns, and then the camera captures it from all parts of this particular mirror. It is focused on the mirrors. Okay, so you can either use a rod mirror, or you can use this arrangement. So, this is a retroreflective shadowgraph.

Uses a very similar principle. This particular thing is very simple. So the shadow is cast, and then all the light is basically reflected. Back to the camera, so the camera is not on that side; it is on this side, and so it is the camera. This is particularly useful because the intensity doesn't lose that much. Normally, you use diffusive screens as well, and then the camera can focus on the screen and take images in a normal shadow graph.

But here in this case, you don't do that. You basically need a lot of light because you are taking images that are high FPS. So that is exactly what happens. So this is kind of the setup that is used in NAL. A similar type of setup is used everywhere else. Now, if you look at some of the images, these are not videos, and you can see that you can see fine structures.

Examples : Retro reflective shadowgraph of Supersonic twin jets over a Jet Blast Deflector
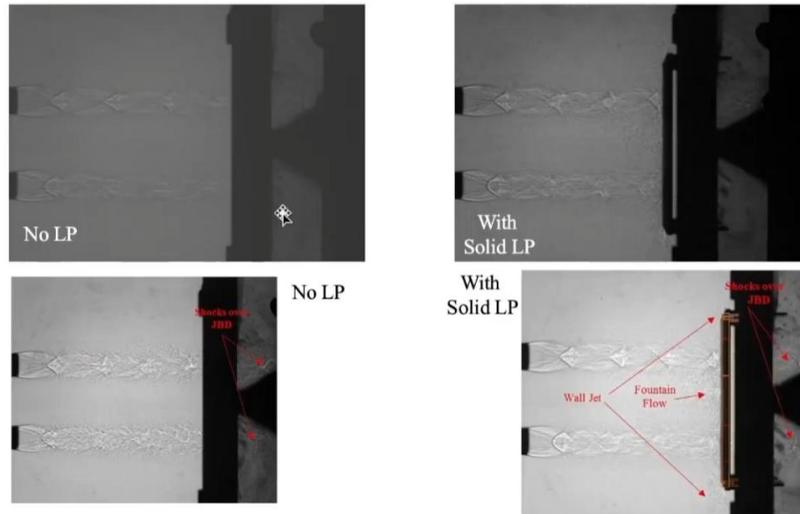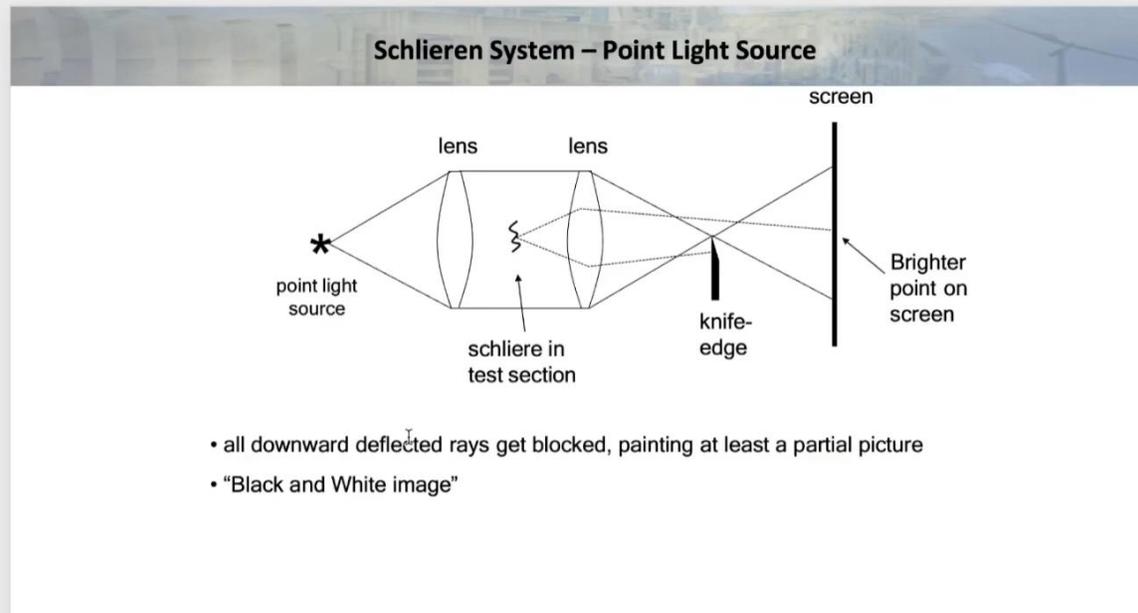
This is, for example, a retro shadow graph of a twin, supersonic twin jet over a jet-blast deflector. Well, actual experiments are not that important, but these are data from NAL, which is the National Aerospace Laboratory, done by Dr. L. Venkat Krishnan and his group. So these are, for example, the shock waves over jet blast deflectors.

And these are twin jets, and you can clearly see the shocks, and you can clearly see the flow. You can see the wall jets; these are the wall jets. Basically, this is like a splash, so this is like a fountain kind of flow. When water impinges, it creates a splash; it is almost very similar to that, so all these intricate features. At very high speeds, images can be captured when you actually have a retroreflective shadowgraph.

So it's a variation of the shadowgraph, but it is called retroreflective. So this is what we have. So, as you can see from the shadowgraphy point of view, a few things to remember are that the second order derivative part of it, and you can have it without any lenses also, which is this. And this happens because of the differential illumination that actually occurs due to the deflection of the beam. And it is particularly sensitive to phenomena like shock where the density gradient is rather sharp.

The gradient of the density gradient is very sharp, and in order to get high-speed imaging done, especially for shocks and supersonic flows, you can actually have a retro-reflective shadowgraph arrangement, which is shown over here, and it can be any one of the other arrangements as well. You can use them now to get these very fine-scale features, and you therefore have a good understanding of what the What the flow does. So this is excellent, and this is how things actually should work. Now we move on to the Schlieren

system. So, the Schlieren, remember, it depends on the first-order derivative of the refractive index or the density, in whatever way you think about it.

Schlieren System – Point Light Source

- all downward deflected rays get blocked, painting at least a partial picture
- "Black and White image"

So what happens here is that there is a point light source, and then you have a lens, which makes it collimated, nice and parallel. So then the Schlieren object just sits here, and normally you have another lens that focuses it back to a particular point. So at the focal length of the second lens, you put a knife edge, which can be a knife edge; it can be a razor, it can be a blade, anything that is sharp. So what it does is that, if you look at it carefully, the chivalry, which is the test section, actually deflects the light because of the deflection that happens as light passes through it.

Now these do not get focused at that particular point. Okay, the other rays will be focused at that particular point, right? And then it will go out again, and then it will illuminate the screen. What will happen over here is that some of the rays, all the downward deflected rays, get blocked, whereas the top ones actually go to the screen. So this will be bright; there will be a dark. Over here, relatively speaking. So you get a black and white kind of image, and all the downward-reflected rays get blocked, painting at least a partial picture of whatever is going on.

So this is the principle of Schiller. So it blocks a particular part of it. So, uh, you know, this is like what we call the boring rays, which are all kind of blocked, whereas the happening rays—those are the rays that are allowed to go and illuminate the screen. So that is, uh, that is, I mean, a very crude way of saying what the Schlieren actually is capable of doing. So it paints at least a partial picture of the situation. Now, if we use an extended light source, this is an extended light source, as you can see.

So there you basically use each one. So the extended light sources are like a series of point light sources. So each point source in the extended illuminated sources illuminates every point in the test section. Each point in the test section is illuminated by rays from the entire extended source. So when there is no Schlieren present, what happens is that if you look now at the row, it is this particular one, so their first lens and second lens converge at a particular focal point, and then the outer rays, the other rays converge to a Slightly different focal points because of the extended nature of the light source.

Schlieren System – Extended Light Source
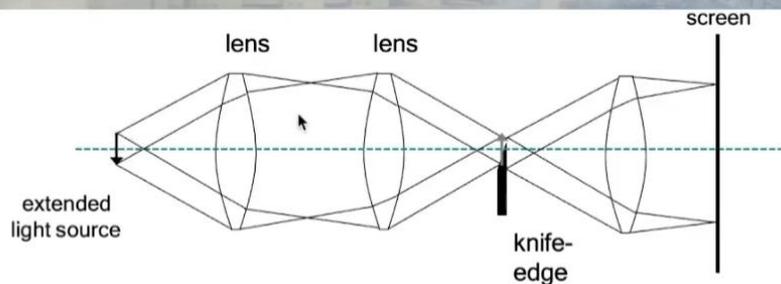
•the extended light source: each "point source" in the extended light sources illuminates every point in the test section → each point in test section is illuminated by rays from the entire extended source

•with no schliere present, if we advance the knife-edge to block more the "composite" image of the extended light source → block each "elemental" source image equally

And so, as you can see, there are two focal points right here. If the knife edge, when there is no shattery present, is advanced to block more of the composite image of the extended light source, then each elemental source is blocked equally. So you can see it here as you move this up. When it is here, you get this kind of image. When you move a little bit up, it becomes darker. And when you put it up to that particular point, it becomes a completely dark image.

So when there is no shielding present, if we advance the knife edge to block more of the composite image of the extended light source, you essentially lead to the blocking of each elemental source image equally. All right. So this is, and this is what is rendered on the screen, as a matter of fact. Therefore, we can see that there is a very sharp dark thing when it is completely moved from this point to that point.

All right. Now you place an object in the testing area. So, this is the object once again placed in the test area. So this is the Schiele read. So there is this extended light source

once again. We have the lens arrangement now.
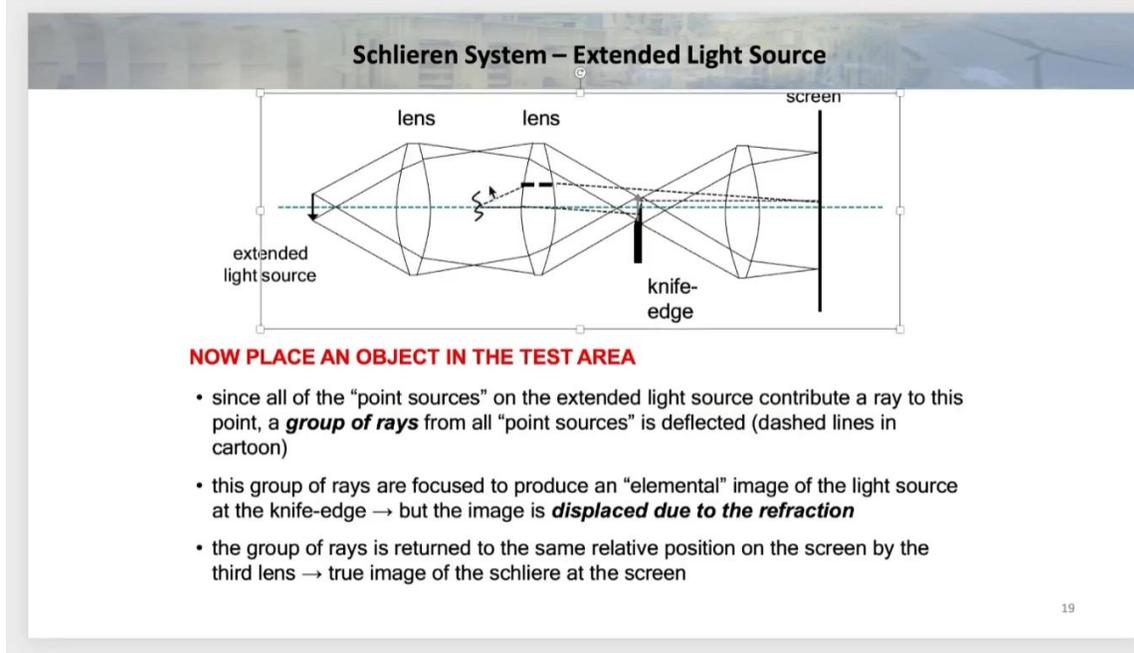
Same arrangement, we have not done anything to the lens. Since all the point sources on the extended source contribute a ray to this group, a group of rays from all point sources is deflected. And the dashed lines are the deflection. All the rays, which are a group of rays from all the point sources of this extended light source, are deflected. As you can see, this is the deflection that we are talking about; the dotted lines represent the deflections.

So they are all deflected. They are all deflected. Now this group of rays is focused to produce an elemental image of the light source at the knife edge. At the knife edge, but the image is displaced due to refraction, correct? So all these rays ideally should have been, these groups of rays are focused upon an elemental image of the light source at the knife edge, but the image is displaced because you have an object now in between, you have the chivalry object, which has deflected the light rays. So this group of rays is returned to its same relative location by a third lens, which is right here. They return it to the same location, the third lens, and this leads to the true image of the chivalry on the screen. So you can see all the other rays return to their original configuration, except this object, which is deflected from the original group of rays, which are basically deflected from their original position, so the image is displaced due to this refraction.

Okay, so this is how you get the effect when you use an extended light source. This is what exactly happens. Now, the displacement of the source image basically separates the rays refracted by the chivalry from the rays. from the rays that provide the background illuminance. So you see the displacement of the source image separates the rays that are refracted by the Schlieren from the rays that go towards the background illuminance.

Because the refracted light is separated and has a different amount of cutoff by the knife edge, you can see the knife edge and recombine in the Schlieren image on the screen; this leads to variation in the illumination with respect to the background. So what happens is that there are many points of varying illuminance. The Schlieren image shows the shape and strength of the Schlieren. So if you look at this picture, this is the undistorted composite source image. And this is the knife edge that we have placed, so what happens is that, uh, you know, a weak source image is displaced by the shielding object, so this leads to the formation of the chivalry on the screen.

The note using an extended light source gives continuous grayscale clarity in images. This is the knife-edge. This is the weak source, which is displaced by a certain amount given by ΔA.

All right. So this is the principle that you want to know. If you now look at the sensitivity, the contrast is given by the ratio of the differential illumination at an image point to the background illuminance. which you already saw. And this is given by the focal length of the Schlieren lens, which is f_S, and then the deviation along the y direction, which is a refraction angle, and a, which we defined in this particular figure, as you can see. And how much it is raised, how much is covered, basically, by the knife edge. And the sensitivity is the output of this contrast, showing how this contrast actually varies with the refraction angle.
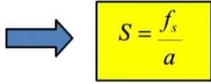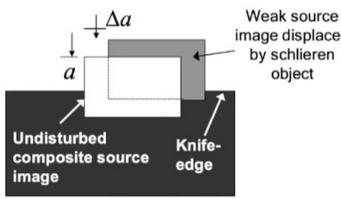
The sensitivity is essentially Fs divided by A. So once again, undisturbed composite source image, you put a knife edge, the image is displaced by the Schlieren object by a certain amount. So a larger focal length actually gives rise to better sensitivity because the focal length is right there. And more obstruction of the image source also leads to better sensitivity, which is basically, you know, more obstruction of the image actually gives rise to better sensitivity. That is what is actually shown over here; you can see that this is the simple principle that you know: differential illuminance at a particular point, this is the background illuminance, and this is the displaced source image that we see over there.

So, two things that you should remember are the Schlieren focal length. Focal length is actually very important, and it leads to the idea that larger is better; you know you get more contrast. Essentially, the sensitivity, however, is also dependent on more of the obstruction of the image source, which is basically ΔA that comes out of this exercise. We would also look at the other Z-shaped Schlieren systems and double-path Schlieren systems in the next class. Right now, at this particular point, I think we should stop here.