Gas Dynamics

Prof. T.M. Muruganandam
Department of Aerospace Engineering
Indian Institute of Technology, Madras

Module - 19
Lecture - 47
High Speed Flow Visualization

Hello, everyone welcome back today's class is suppose to be on flow visualization, till last class we were dealing with how to measure pressure or mach number in the flow. Of course, I did not tell you about temperature measurement, temperature measurement is always using some thermo couple or some such device, which will always be giving you only stagnation temperature, and never a static temperature. Unless you are having a thermo couple flying along with the flow and measuring, it for you which is not easy for us, so it is always going to give you only stagnation temperatures typically for us.

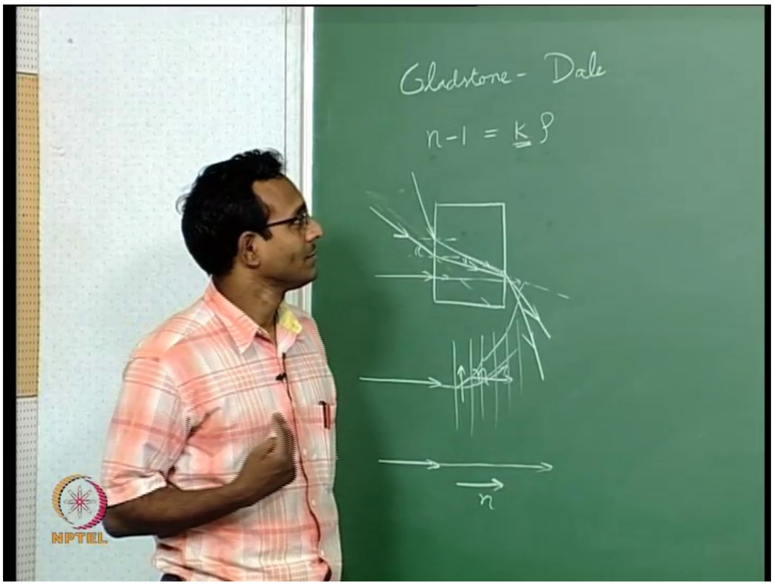
So, I did not deal, so much with it that becomes a experimentation course separately, I do not want to deal with that in details here, so the next thing we will go into is flow visualization. I have already shown you I believe shocks around bodies once, we will go and look at it again, at now will understand how we are able to see yet and then will go and look at it again. If you think about I want to visualize flow in low speed flows or incompressible flows, typically the common thing to use is put smoke in the flow.

Then you will see these smoke particles going around, where ever it goes that is the direction in which the flow is going that is easy to tell. Typical simple flows we can do that and the flow velocity becomes higher and higher, the rate at which you need to send the smoke will become extremely large, otherwise you would not see anything clearly. And even then that you cannot be sure, that you are able to seat the flow all the way into wherever you want.

I sent smoke from one corner it may just be along the wall and not going into the flow, that may also happen in high speed flows need not be supersonic even subsonic it may not work very well. So, but one good thing about this compressible flows is when it is mach number is more than 0.4 or, so you will start having reasonable density jumps, when we have reasonable density jumps. Now, we have to think about can I really use this density jump to visualize what is happening in the flow, can I see the density mapping in the flow that is the idea.

When we start thinking about this, we should first know that we can see only if I want to see things it needs to be a transparent medium. And the next thing I want to tell is there is something called glad stone dale formula, which is going to link the refractive index of that transparent gas this works for only gases typically.

(Refer Slide Time: 02:44)



Glad stone dale formula which is linking the n refractive index of that gas to the density of the gas, where k is the glad stone dale constant, just this glad stone dale constant what it is telling me is basically. The refractive index of the gas depends on the density of the gas rho, so if this is the case I am looking at this formula, and I am going to tell that refractive index is directly proportional to density. Linearly proportional directly proportional to density, if density increases refractive index increases, now how can I use this property to visualize what is happening in the flow that is the next question.

Now, we have to go and see what can I do with refractive index change, I will recall some experiment which we did long, long time back that is everybody must have done it in physics experiment in high school. If you send a light ray at an angle into a glass bar, glass big block it is going to turn towards the glass, instead of going straight it has gone more towards the glass. And if the light is coming in from inside the glass to outside, it is again instead of going straight going to turn towards, the glass in both cases it is turning towards the glass.

Refractive index of glass was of the order of 1.3 to 1.4, and outside air, we assume to be 1.0, ideally it is 1.0403, something like that we assume it to be one this is what we did in physics in high school. And we would have done this experiment, where we say that we put this as angle of incidence, angle of refraction and we would have done this whole refraction experiment. What we want to observe from here is that, light always wants to turn towards the glass, the reason being light wants to turn towards the higher refractive index medium.

That is the main sentence I want to make, light wants to turn towards the higher reflective index medium, each ray of light if I sent another ray of light here, let us say I will send it some other angle also, I will send it at a very steep angle. It is going to turn some angle and then it is going to go straight into it, and then it is going to turn out almost I say, in fact exactly the same angle as the incoming angle this is our refraction we would have done studied.

Typically, you will see this in aquariums, we have big aquarium and you are seeing through the water at an angle, you will suddenly see the fishes somewhere else, and if you moves sideways you will start having some headache in your eye. The primarily, because you are causing some trouble to your vision, it is brain is trying to predict some movement of the fish, but it is doing something else. So, your eye is straining to do something extra, that is why you will feel that eye gets strained a when you are looking through a aquarium at an crazy angle.

If you are seeing perpendicular nothing goes wrong, same thing you can see it in aquarium every day, if you going and seeing a straight through there is no refraction, that is one more thing you need to point out here. Light just goes through straight into the glass, and it comes out of a glass also straight through, so what I have to now look at is unless I have incidence angle other than 0, I will not have any refraction. Now, the ray to look at it from my point of view it will be if there is a light ray coming, and it is seeing a density or a refractive index gradient, perpendicular to the direction of propagation of light.

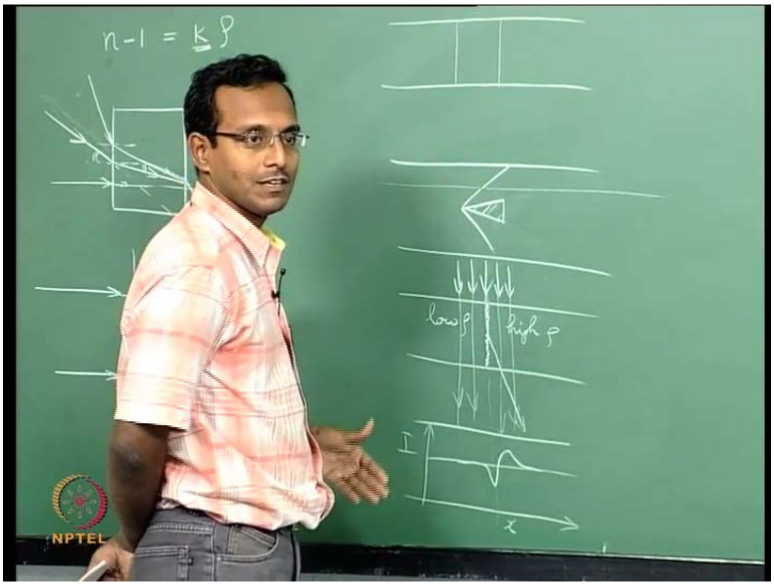
The refractive index gradient perpendicular to n increases up let say as I go up n increasing, if I have such a case then light will bend towards denser medium, that is a idea. If it is only a thin slice of course, it is going to turn some amount, and then it is going to turn back it will turn into this, and then it will turn back like this something like this will happen, but if it is going to be a whole set of things continuously like this. Then it is going to turn a little bit more, turn a little bit more, turn a little bit more, and finally go out somewhere else.

This whole thing will start happening if it is so happens that the density gradient is a the refractive index gradient, I am interchanging the words currently will just look at reflective index, will go to density after this. If density refractive index gradient is only along this direction, n increases along this direction or decreases along this direction both are fine by me. In both these cases I will not have any deflection of the light it just go straight, but if I have slices of regions, where n is increasing this way, then the light will bend towards denser higher refractive index.

Now, I will link this two statements which have been missing up all this time, density is directly proportional to refractive index, so wherever I said refractive index I could have replaced it with density, light bends towards higher density. When the density gradient is perpendicular to the light propagation direction that is the overall idea, how much does it move it depends on from gas to gas, if I say that this k it matters.

If my density gradient is some value, this is proportional the refractive index gradient is proportional to k times that value, it is proportional to density gradient. And this constant if it is high, then that gas will have lot of co lot of correlation between density and refractive index, let see idea typically most gases we can do this experiment.

(Refer Slide Time: 08:57)



Now, the way we want to look at it, let us say I have a shock in my flow and say this is my test section of my supersonic tunnel, flows like this I have put a body like this. So, the shock is going to be up and down like this, let us say I am looking at the ventunnel instead of looking from the side usually, I am looking at it from the top. Now, if I look at it from the top I will draw both views, this not as good I will draw both views that engineers will easily understand things, and we put to views, let us say I have a wedge here in flow and we know that there will be a shock here.

Let us make my wedge smaller, I do not want to reflections to come back and hit my model some such thing, I have wedge in flow and this particular thing will be just a line when I look from the top, that is this view. Let us pick a line like this, I take a cross section like this, if I take this cross section and look at it from the top what will I see I will draw that at the bottom. Now, I can draw it on this it will just be messy, so I will draw it at the bottom, again and I am going to say that it is going to be a line here with low density this side and high density on the other side this is what will have.

Now, if it, so happens that I send a light beam, that is I am sending light beam along the side of the way, along the side of the way along the span of my of wedge, if I send it like this in this plane it will look like it is coming this way, I want deflection. So, I will make it come this way I am sending parallel beam of light, something like this I am sending, so many rays of light coming down, what will happen to this particular ray, that is coming here. It is going to see, yes there is outside air this may be some other density there may be a density jump, but this is coming perpendicular to it, so not much change it just goes through straight.

There is no density gradient this way perpendicular to propagation direction, so the light just goes straight same thing happens for this one, but for this small region in near the shock, that particular light ray that is coming in is seeing that, there is denser medium this side. This is low density this is high density and this is my shock, I will make my shock this fuzzy line, this is my shock what will happen this light comes here, and then it turns in because is likes to turn into denser medium.

So, it turns in after it turned in, it is not seeing any other change it is all constant density, so it will just go straight no more change, and then it is going to come out somewhere else. So, what I am effectively seeing if I put a screen somewhere here, I am going to see initially if there is no shock and all the densities are uniform, there is I do not have a flow situation. Then I will just see that the light that is coming parallel will just keep going straight and it will fall on a screen, all intensities equal let us say I said in all intensities equal, I will get all intensities equal at the end.

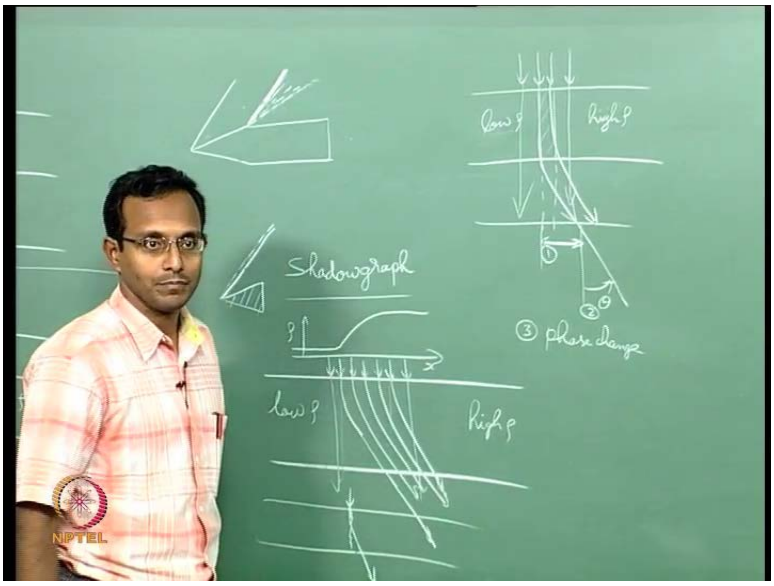
Now, if I have my flow and I have a shock at that location from that particular height, then this particular beam alone instead of going and eliminating this point, it is now gone somewhere else which means this region will become dark, but some other region will become bright. What is essentially happening is if I plot intensity verses distance for before and after, if I say before was like this straight line all intensity equal everywhere, I got a very good light beam where it is all uniform light everywhere.

Now, because there is a shock at this location I am going to have a condition, where it will be low and high somewhere else, remember that the net integral of light intensity should be the same, because it is the same of light that is coming. It is just rearranged light is just rearranged inside here, and you will get something like this, now what does this mean when I have intensity low intensity high.

When I look from this side, this is my side view, I am again going back to side view what did we talk about we said light is coming from behind the board to this way towards us. And I am saying at that location there is light coming very close to the shock deflecting to downstream direction, that is what has happen, so instead of coming here it is now gone somewhere else.

Say I put a screen somewhere this far, then I am going to see that the light is deflected, so much, so this region will be dark and the next region will be bright, similarly every location here is going to do that. So, what I will eventually see will be, initially when I look at it without any flow, I will just see a shadow of this wedge this triangle alone will be a shadow.

(Refer Slide Time: 14:36)



Now I am seeing new things I am seeing some other region I will draw this picture again here, initially I will just be seeing this shadow, but because of shock being along this line I will draw thin line. If this is the shock I am going to have, I will draw a dotted line and the solid line, I am going to get a line where it is dark and the line, where it is bright.

I am going to get this, because the light that was supposed to have come here has now gone there, so this region is having less intensity and that how much ever is less is now gone to this region. Now, it is more bright than what it should be usually without the flow condition, so now, with the flow it is the light from here has gone to this position. So, what we are seeing is an extra shadow, some other dark region shock is causing this shadow, so this is what a people call as shadowgraph.

If we take a picture of this, that is my it is like photograph shadowgraph, I am going to have photo of the shock sitting in here, what if I have an expansion do I have an expansion here, yes at this point. I will draw a better model than this, say I will take a different model, I have this model I do not want to talk about what is happening behind, so I have expansion here, and this is my shock.

If there is a shock that is going to give me, similar to whatever is happened here dark line followed by bright line, now if I think about this particular location, this is not a sudden jumps it is a slow change in density. So, the density gradient is not strong, so the deflection of light will not be very strong it will be weak, but there will still be deflection.

So, if I look at this particular location, what will the light do if it is coming from inside the board towards here, it will turn towards the denser medium, where is the denser medium, this is denser, because it is expanding this way. Density decreases as I go this way, so light will turn up stream, because of that will start seeing this region very bright, and it becomes darker and darker.

As, it goes through it is a slow gradient, light from here wants to go there, light from here wants to go there, light from here wants to go there, light from here wants to go there, because it is a slow gradient, it is continuously changing. And after this line density is all uniform, so there is no more redistribution of light intensity it just goes straight, this is what happens in there. This is one way of simply visualizing the flow, all I need to do is send a parallel beam of light with uniform intensity, that is what I need for this particular thing.

Now will think of a more crazy situation, instead of having this simple situation I am having a case where, we talked about a shock initially, where we said low density high density. Now, I am going to say density is not jumping suddenly across this line, but over this whole range density is slowly changing, if I plot density verses x here. It starts with some low value, it rises up and become constant, there during in this band it is slowly changing like this.

Now, if I think about what is going to happen light rays are coming this way, this final light beam see no difference, it just goes straight this one just goes straight, now the remaining lines this is going to see the second beam is going to see a higher density to the right. It turns, now it is going like this and it again seems the higher density, there it will turn more, it will see higher density there it will turn more, it will keep on turning, and it will go end up somewhere else finally.

Similarly, all of these will be turning, but after this line it is going to be just straight line, because we said after this its uniform density, so it just turns only up to here and then it goes straight line some such things will start happening. If it is just one sudden jump all that jump occurs in one point, if it is a uniform jump it is going to change slowly out like this, as suppose to a shock, if I draw that picture below it.

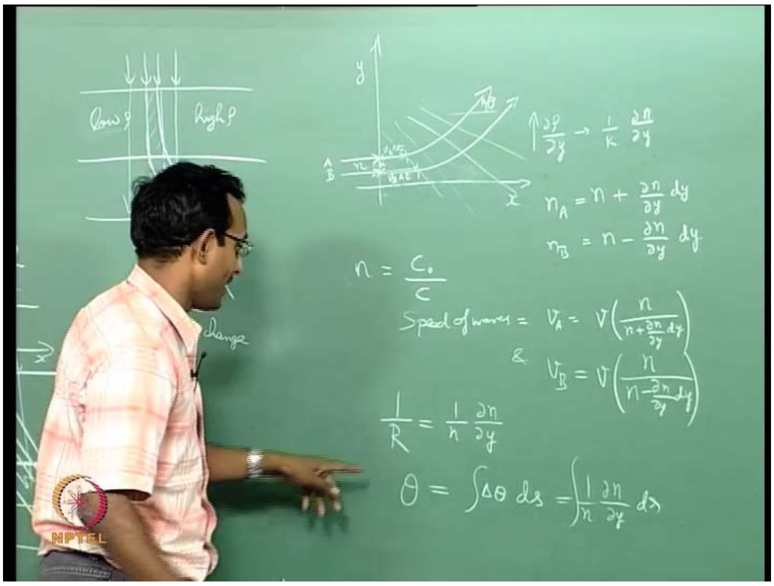
And this is my shock only this line is now going to be, when it comes and hits it is going to turn like this, is a sudden turn while the other beams are just going to go straight. In this case it is a slow uniform turn, slow turn all the way around that will also happen, now what all can I do with this information I can of course, find the total deflection from the original path to the new path at some distance.

I will draw another picture somewhere here, let us say this is my small band of density change, I will put low to high low density to high density, and I have parallel beam of light coming this way. This is my screen let us say at some distance, then I can think about instead of going straight, it went by this much distance, I can think about the net displacement of these lines, that is one quantity I can try measuring. And that will tell me inference of what is the density change inside, that is one thing I can do or I can now think about what is the final angle at which it is coming out, what is the final deflection I can either measure this.

That is one the displacement from the original location or the angular displacement from the original direction of propagation of light, or the third one, this is the second one third one I can think about phase change of the light wave. Why do I say there is phase change when waves travel through different refractive index medium, what will happen is it will oscillate with the same frequency, but it will travel with different phase.

So, when it comes out if I think about a case where it did not go through the higher medium, verses the other case it went through the higher medium, these two waves will not have the same phase difference at the end, it will not be 0 phase difference there will be a non 0 phase difference at the end. And that can also be used to infer that there is a density jump, ideally what we are inferring is only refractive index jump, and which can be taken as density jump, because of glad stone del formula, which we started with today.

(Refer Slide Time: 22:47)



How will I use this from mathematical point of view, I am going to say I will start with this is my y direction this is my x direction, and I am sending light along my x axis. And I am going to say there is a gradient this way dou rho by dou y, which is related to 1 by k dou rho by dou n by dou y, this is coming from glad stone del formula. Of course, actually what I want is dou n by dou y from the deflection, from there I can go back and find out there is a dou rho by dou y whichever way you look at it.

If I say the density gradient is uniform along this direction, that is it is a constant dou rho by dou y I am assuming, if I say it is just a constant dou rho by dou y density is increasing linearly, if I assume that. Then we can write things like I have a beam a and a beam b coming in, I can write where n I have written the refractive index as seen by these two beams, when it comes to this location, where the change happens.

I am saying at this middle point my refractive index is n, and I am saying small d y that side verses this side, this will be the change I will see. It is just a calculus simple calculus, now we know the relation between speed of light and refractive index, that is n is equal to c speed of light in vacuum divided by speed of light in the current medium for which we gave this refractive index.

So, if n is large c is small that is if n is large it is thicker medium, denser medium high refractive index light travels slowly through it, that is what we to think about it. So, speed of waves if I think about v of a, then this going to be equal to v times n by n plus dou n by dou y d y. How do I get this I use this relation along with this relation, this and this together I will get to this point, where v is some general speed at that middle point of course, I can link it to c naught also if I need I do not want to do that. And similarly v b the waves speed, the electromagnet waves speed at the beam location v it will be n divided by n minus dou n by dou y d y, it will be this.

Now, because these two velocities are different, what will happen eventually I am suppose to be looking at wave fronts that is the real idea, why the wave turns why the light beam turns is because the wave fronts are different. If I tell that speed of this one which is higher here v a or v b assuming dou n by dou y is positive, this is higher why this number is smaller, so this is going to be higher speed then that. So, what will happen is if I think about one wave that is I waited for one wave frequency time, that is going to take it would have travel this for the other one.

I cannot talk about frequency here, I have to talk about time, I do not want to put a wave there I will just say from here, to here it has travel in some delta t v b times delta t, some small delta t, I am picking. The same time this one would have travelled only lesser v a times delta t, but at the beginning at x equal to 0, both were having the same wave front, they were both say the peak of the electromagnetic wave or something. I am tracking only the peak the positive peak, let us say I am tracking only that now the positive peak has gone here and here, if I think about that that becomes my wave front now my wave front has turned like this.

Now, physicist will come and say electromagnetic waves trap propagate in such a way that the wave front propagates perpendicular to itself, the wave front will now travel this way. So, later the wave front will become this, then it will become this, then it will become this if there is no more change, if there is more change then the next delta t later it would have gone only this much this would have gone even more.

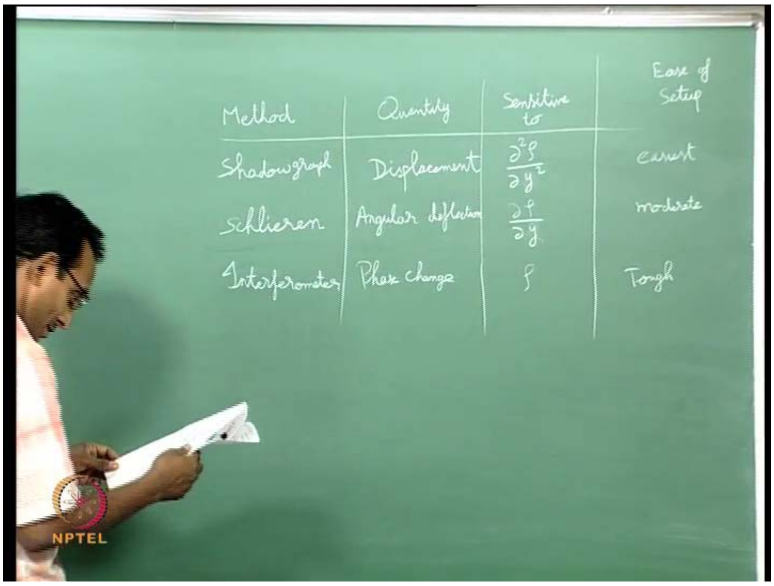
Then the wave front would have tilted more, that is the case per our current experiment, so it will not going parallel to itself, but it will turn more. What happens is the wave front will start turning more and more, this is equivalent to saying my beam of light is going like this, verses in this case is going like this is what will actually be happening. If we look at from ray optics point of view verses wave front optics point of view, it will be the other way you know that light can have ray nature or wave nature, we are using ray nature verses wave nature will typically be using only wave nature.

That is enough for us, now it can been shown that you know that the curvature, if it is if it a strong curvature it turns to first then the density gradient is high, if it turns slow then the density gradient is slow. That you can tell directly right from in tuition at least, now I will say I give you this relation, I am not deriving it fully, but it can be easily derived, it will take some 3 4 steps extra after this point to derive to this point, I am not doing that.

But, it can be shown that the curvature 1 by r is going to be given by 1 by n dou n by dou y, if dou n by dou y is 0 R goes to infinity, which means this circle has infinite radius which is equivalent to say it is just going straight, dou n by dou y being 0, means it will just go straight. That is what you are having finally, now I want to say find the final deflection angle theta, how will I find that I have to integrate each individual delta theta finally, I will get the total theta integrated over all this x.

So, that is going to be net theta is equal to delta theta integrated in d s, I am writing here not d x, because I am following the light ray, I am going along the light ray path and integrating along that that is d s. If I do this can be written 1 by n dou n by dou y d s can be rearranged to this particular form, I did this kind of analyses 1 by R is delta theta kind of analyses, when we did Crocco's theorem also. It is a same set of expressions it is just the previously, it was velocity stream lines, now it is light path ray that is all there is nothing different there, but the expressions are the same math is still the same for both of these cases.

(Refer Slide Time: 31:17)



Now, I can get theta in terms of this, now I will tell you some extra information I will just give you a table, where I will say the type of method used what quantity, you are tracking sensitive to what, and ease of setup. I am going to make a small table shadow graph, I have not shown you the setups yet, I am just showing you just the techniques on the whole first. Shadowgraph looks for change in displacement of the light ray what we talked about at the beginning, light ray instead of coming straight it has now displaced, so much on the screen that is what is given by this.

Next it is sensitive to dou square rho by dou x square or actually for us we wrote it as dou y square, so will put dou y square what it really means is it is sensitive to second derivative of density perpendicular to the light propagation direction. That is what matters here, and ease of setup easiest, this is a easiest to setup, next one Schlieren there is a confusion about whether Schlieren is a name of a person or whether it is just a general word should it be capitalized or not.

I saw a recent paper which said that it is not very recent I think I just found it recently, where I found that Schlieren suppose to be somebody's name, and it should be capitalized itself that particular paper. I still have the paper on my computer it says that is actually a name, but it, so happened that Schlieren came to be used as meaning fuzziness.

If you the way they found it is when they were making glass the way, they make glasses they will make molten glass liquid flow on some colder surface, and let it settle they will cool it. When they cool it this becomes a big sheet of glass, if there were waves in the glass while it is settling, the glass liquid while it is settling, it will settle as if with different thicknesses.

Now, because each region has different thicknesses it is like you are having a glass slab with varying thicknesses, it is forming something like a lens, because of that. If you look at parallel beam of light coming from somewhere the lens effect will focus the light to some point, so I will see something different on the other side. And this particular phenomena knows label dash Schlieren effect, it is something to do it German I do not understand the full meaning of Schlieren really, but they told that that particular paper told that this is a somebody's name also.

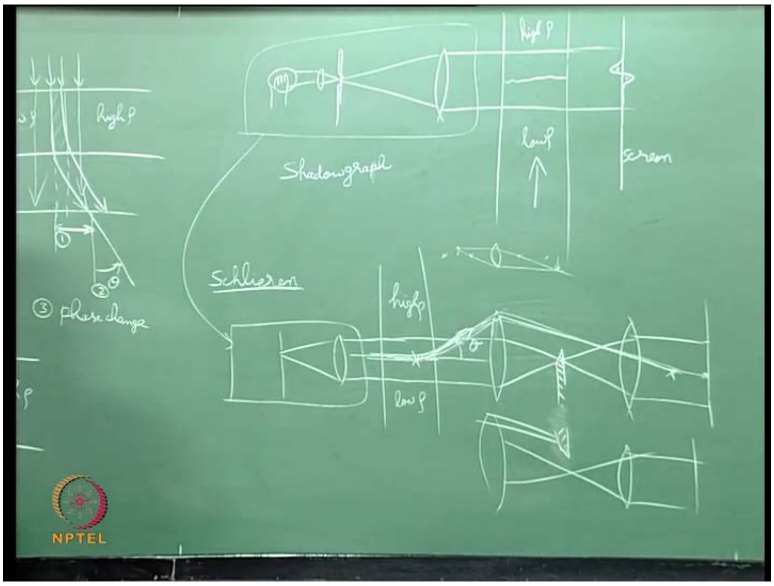
This looks for angular deflection displacement same thing angular deflection of the light ray instead of the light ray coming straight away from the board. It is now going at an angle from that original direction that is what just tracks, and it is sensitive to first derivative of density perpendicular to light propagation direction and this is just moderately difficult.

First one is very easy, second one is moderate; that means, the third one is tough, interferometer this tracks phase change, we talked about three things that can be used for tracking we labeled 1 2 3 before. Now, that comes as 1 2 3 directly here, and this looks for actual density values, it is sensitive to density, and this is tough it is not as easy as the other things its needs more alignment, you have to more parallel exactly parallel etcetera.

And you have to think about light intensities before and after, lot of things to think about, so we have not seen any of the setups yet, but I am just telling you easiest to toughest kind of setup here. Now, we will go look at shadowgraph set up, I already talked about it a little bit, but we will go look at it formally.

We already have the set up here in this picture itself, so I will start here, but I will any way go and draw the picture, if I think about only this portion, there is some flow with low density becoming high density. And I have parallel beam of light coming this way, as a whole set of rays of light coming this way, they are all equivalent intensity I assume. And then when it come this side I put a screen at this point, what am I seeing I am seeing this light ray comes straight, this point lost its original light before the flow started there was light falling here, now it is not there, but some other point got extra light that is the idea.

(Refer Slide Time: 36:58)



So, how I will form this set up, I will have some bulb typically put a lens, focus it to a point put a pin hole, so that it becomes clean light source it becomes almost a point source. Then it will be better for using parallel beam set ups from here, this is a pin hole, typically pin hole is represented like this, and I will put another lens make it parallel beam. Now, this parallel beam is going to go through my test section, say the flow is going this way low density, high density and this is somewhere where my shock is present or something.

Then on the other side I will just have to put a screen, this simple enough set up parallel beam of light coming in through this test section, perpendicular to the test section walls, then it comes out the other side and it will be like this. What if it is not perpendicular to the test section walls and its coming at an angle, what will happen if my light beam is not going like this, but going at an angle like this, now there will be more problems, every light ray will see this sometime or the other.

If I send light beam like this, one will just go it will refract go out, there is no trouble this one here will refract go out no trouble, but there is a whole bunch of waves in a middle, which will go refract. It will go hit this shock somewhere turn more, and then go out somewhere else, the shock will be spread out more, if you want to get very thin shocks which is what is the reality, I have to take the experiment and do it straight this way perpendicular.

So, for this particular situation what should I see, light is going to bend towards denser medium, so I will see intensity going high, low and then coming back like this is what I will get. This is I will put a plus and a minus intensity increases, their intensity decreases here, and that is what I will see for a shock, this set up is a shadowgraph set up, next we will look at a Schlieren set up.

This one again this part is exactly the same, I do not want to draw it again let us say I have this block of parallel beam optics, I am finally, going to have this parallel beam that whole thing is present here. I will why not I will just finish this parallel beam of light coming out of that section, and now I will put a test section here, now I have draw it such that I need more space that side. So, parallel beam of light coming this way, let us say my shock is sitting somewhere here, high density low density something like this.

Now, the light beam that is coming here is going to be, finally deflected at an angle from the original, now whatever beam that are coming here, they are all going to be turning only if it is very close to this shock region. So, now, I will start doing something else I will put another lens here, if I look at only this deflected ray it appears as if it started from somewhere, something like this and it came out like this.

Now, that ray when it comes out I put up big enough lens for covering that, need not be I am exaggerating all these angles the actual angles are small I am exaggerating all these angles, so that you can see it clearly. So, it deflected now for this lens it is as if it is some distance away, typically I have to put this far enough that it is more than the focal length of this lens, so it is between f and 2 f this optics you should know.

If I have a lens f 2 f, if I have an object in here, you should know these already from physics, it is going to form a final object far away. So, it is going to form an object, somewhere else compared to I have the other parallel beam of light coming that is also going to see the lens. What will that do, it is going to go to focus somewhere else, it is going to go to focus here, instead of thinking about this has one ray, if I think about this as a small beam of light.

Then that whole beam of light is going to be going and focusing somewhere far out like this, now think about I am doing something special, I am going to take this whole thing, put another lens and make it parallel beam and go to a screen. I did something like this, let us say if I did something like this, then the parallel beam will just go back as parallel beam on the screen, so all uniform intensity everywhere.

But, that little bit of deflected light is going like this inward, and it is seeing another lens, so it is going to finally, go end up at some other location slightly different from what it wanted originally, if it was going straight this way. Now, I will think about one more thing, I am not done with this, I want to now think about putting a knife edge or actually something to block the light, I am going to take a knife edge or blade.

I am going to put it through this point and block this region, if I block this light that is coming from the parallel beam. I will see only this light going there, because that light is just deflected far away, and it is just going through straight, there is no trouble with that the light that was going straight un deflected will all be blocked. So, what will I see at the end only the regions were there was light deflected only that light will be imaged, wherever there was light deflected, there will be a bright spot everywhere else it is dark.

So, I am going to see wherever there was a shock, in this case it is deflected this way, and I put knife edge this way will come back to that again it is deflected this way and I put knife edge this way. I am going to see only, wherever there is density going up that will be visible there by the way if I did the opposite.

I will draw that picture alone separately, if I did the opposite and put a knife edge at the other way, and I have a set up like this, what would have happen from this lens that deflected beam is not going to go through. Deflected beam alone is blocked and the other light is shown, now what will happen where ever there was a deflection, that alone will be dark every were else it will be regular original intensity. There will be a small drop in intensity, because that light is also dropped, which is again going to be at the same location, because I am expanding, contracting, expanding parallel to the original one.

So, if I do this kind of knife edge arrangement, then I am blocking whatever is deflected, if I do this kind of knife arrangement I am allowing whatever is deflected, that is the good thing about this kind of set up. I can either see the shock as bright or see the shock as dark, I can choose to do whatever I want in this set up, this is your Schlieren set up arrangement.

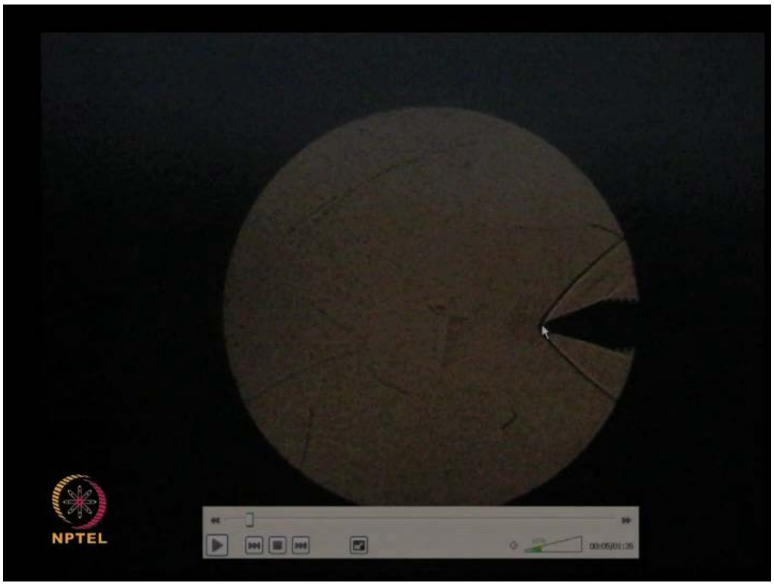
So, if you want to think about how to increase my sensitivity, I have to have this focal length very, very long if I keep my focal length long, what happens is even if there is a very small deflection, there will be a huge change in this. This will be deflected more, the beam that is having any deflection will be going far away from this when that is happening, then now I can put the knife edge at the same location, if I change the focal length then it would have gone.

So, far out then I will see more intensity of light coming out, that is about sensitivity of my Schlieren set up, Schlieren set up typically people use long focal lengths. We have Schlieren set ups which are like having mirrors instead of lenses, we have not drawn that picture yet, this particular lens, if you think about focal lens. I have used one which was 6 and half feet long that is the kind of lengths people will think about, at least we should think about more than one and a half meters typically.

And what should be the diameter of this, that is decided by what is your test section window size how big do you want to see, if where is my flow set up, let us say this is my flow set up and I am seeing from the side. If I want to absorb only this size I need a lens of that size, if I want to absorb this big area, I need a lens of that big size that is how it will be working.

If I think about of flow in a test section with a wedge there and I want to see this whole region, I need to have huge lenses or mirrors that is also needed. Now, in this reaming few minutes, I will just show you a movie will come back to set up for interference later interferometer, in next class I will go to the screen.

(Refer Slide Time: 47:47)



What we are seeing here is first I will show you, and then you can see its actually an ordinary screw, metallic screw, mild steel screw, which is been ground off in the sides to get the shape as a wedge, because it is a screw. And it had threading before we grinded off, it is having steps on the sides, on the edges it is flat portion, those grooves because of those grooves you can also see the mach waves inside here in this region, will see tiny waves which are creating small disturbances.

It is like a small hole and back to normal kind of situation and, so you will see those tiny things it is not very clear, it looks like on the screen, but you can see very clearly the shock that is formed. The oblique shock attach shock that is formed for this particular flow field, you are seeing as a this is actually a shadow graph, so you are seeing it has a dark line followed by a bright line that is the first thing, I want you to notice.

And the sound shows that typical sound in when you are running the tunnel this is the sound in the lab, and you can see the mach waves clearly now, you can also see the expansion wave sitting here. You can also see a band of lines that are together that are the expansion waves also it is not very, very clear in this picture, but I will show you another picture next which will show a little more of expansion waves nicely.

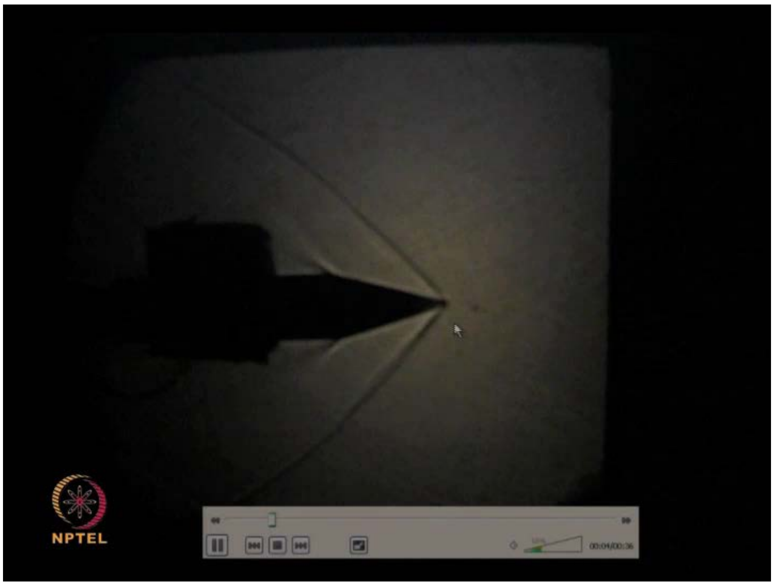
And I want you to absorb one more thing towards the I do not know, why I did not see it very clearly watch this region. If you I am wanting you to look for something, which is the starting shock of the starting of the tunnel, you know that shock will have to go through this full region. We will see some fuzzy thing moving like a ghost, suddenly it goes as it goes fast this shock develops across here, you will see it in one more movie, I am going to show today any ways this look for it now just develop.

(Refer Slide Time: 50:49)

It is just a little bit too fast I will play the next movie, now this flow over a sphere, and here you can see the shock moving and forming the bowl shock here, you will see somewhere here the shock moving and forming in. See here, now as formed now, and now you can see again dark, bright for the full bowl shock, you can also see the expansion fan starting from the point, where it becomes sonic line. After that you can see the expansion fan out like this, and in here for the flow stop, you can see the expansion going this way and the same thing is happening in here.

If you notice this shock is stopping somewhere here, this is because they are decreasing the pressure p naught in the test in the settling chamber, and because of that you are having the shock the starting shock now coming backwards. As, it is coming backward it is erasing the flow and going back, this way if you notice it is just going back.

(Refer Slide Time: 52:08)



This is flow the other way, here you could have seen the shock moving slowly, here you can also see the expansion fan, and also the mach waves you are seeing thin lines coming in from this sides. The way we got the thin lines here and here, etcetera are by putting thin grooves on the nozzle, so we use that to form these thin lines will look at more next class see you people.