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

Module - 23
Lecture - 54
Unsteady Flow Phenomena Video, MOC Simulations

Hello everyone welcome back, we were looking at various features which you have to think about for unsteady gas dynamics, unsteady wave motion, if you are thinking about, and where we were talking about different properties of the unsteady flows, different parts of unsteady flows. Now, overall if we have to go and analyze big unsteady flow problem, you have to go and deal with each of these individual components at every location, then overall it will be satisfied that is what we are trying to do here.

So, as we think about these flow problems we told some set of things like if wall moves into the fluid, then it creates a compression from that point etcetera, and these waves will keep travelling all the way up to infinity or go into some other wall. And when it goes into a wall, typically it will get reflected that is one way of looking at it, another way of looking at it is it goes into a wall, that wave vanishes and then the fluid behind will have some velocity which is different from the wall.

So, that will create a fresh wave from there, because if I have a shock going to a wall that is vanishing after that, but the flow behind it is going this way. And flow is going into a wall or equivalently wall is coming against the flow locally, because of that it will send a compression wave, that can be thought of in two ways. One is the shock goes and reflects back or this shock vanished, and a new shock got created and it is coming out this way. Similarly, I can talk about expansions, expansion wave goes there, it induces flow this way, but the last fluid element cannot leave the wall.

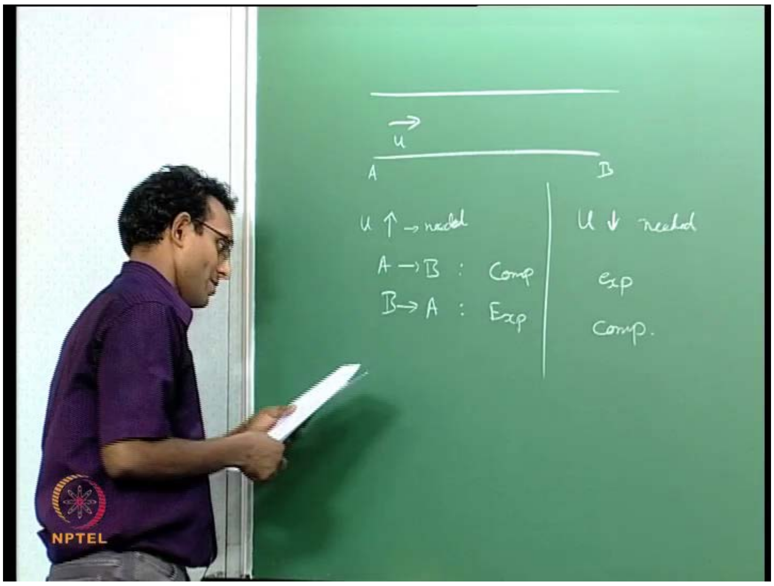
So, that creates an opposite expansion, that will go this direction which will pull all the fluid back this way, that will also happen you can think about it in neither way it should work both ways. Now, we can have some special situation in this kind of the way of thinking, where I can say that if a wave is going in one direction, and wave will travel with some particular velocity. There could be a condition, where the fluid is going straight against it, and the wave velocity is equal to fluid velocity, in which case it is like some person running on a tread mill.

It will just be he will just be standing in one place and running for the external observer, but locally the belt is running and the person is running continuously. Same thing may happen the wave may be that person running and the belt may be the flow, that can still happen and it will look finally, as if the wave is running up stream, and the flow is pushing it down stream and I may come to some equilibrium.

This is what typically happens in all our steady flow cases, if I say there is a shock in my divergence section of my nozzle, actually what it means is the shock is continuously trying to run up stream. While, the flow is continuously pushing it downstream the flow induce the regular flow in the nozzle is your belt, and the shock is the person running on the belt, that kind of situation will come up naturally.

So, that can happen typically it happens with shocks most of the cases not much with the expansions, but it can happen special cases even with expansion. If I can want if I want I can create a flow like this some special case, I have already told you only way to increase or decrease pressure, in a gas at any point is only through compression or expansion waves respectively.

(Refer Slide Time: 03:46)



So, now, the next thing I want to think about is change of velocity, how can I change velocity in a duct, I will think about just straight duct right now, I will talk about diverging and converging after some time. If I have a straight duct and let us say the velocity here is u then in this direction, then I will mach these 2 point A and B, so that it is easier. Now, if I want to say I want to increase the velocity here, and I am sending the wave from the from A towards B, what wave should it be, that is what I am thinking about u should increase, this is my final outcome.

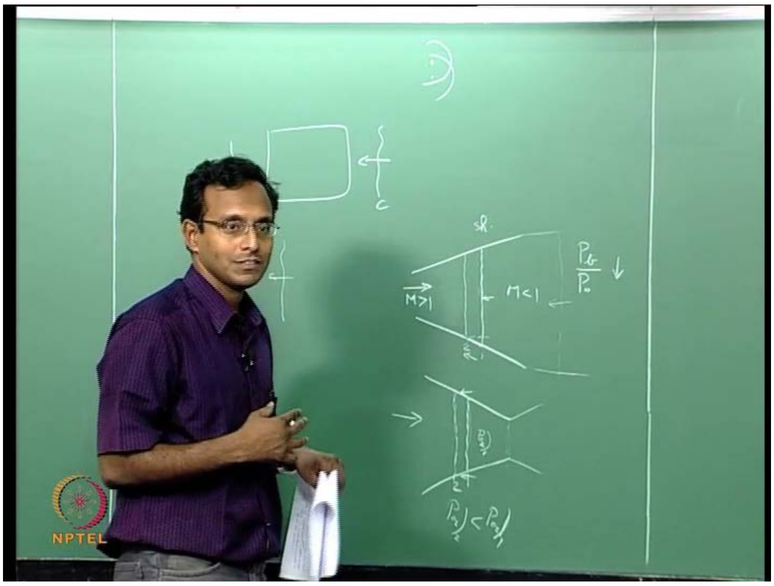
This is what I want needed what all can I do, if I am sending a wave a towards b then that wave should induce a flow in this direction, which means the wave should carry the flow with it. So, it has to be a compression wave, it should go and tell lets go along with me, all of you guys come with me that kind of thing, it is like there is a snake there everybody run this way, remember we used to discuss like this.

So, it will be something like that, so from a to b if I have to do it has to be a compression wave or if I am telling the opposite, if I am telling I want to accelerate this from B to A making a change at B. And that causes the flow to increase in velocity, that can be done by expansion, it is going to suddenly tell there is a empty space here, lets come faster come and fill it faster.

That is the opposite thing, then if I have to talk about if I am sending a wave from B to A to effect finally, u increase then it will be an expansion wave. And of course, the converse will be true if I put u should decrease, this is what is needed if I say this then it will all be opposite of it expansion and compression, it will just become the opposite of it. And this is very useful and thinking about what can happen in a situation, very nice to use these kind of simple ideas in a very complicated situation, in unsteady situation, if I want to increase velocity.

I have to send one of these two waves, which one it depends on whether it is coming from upstream or downstream, where I am making the change it depends on that. While, if it is a steady flow condition, nothing changes anywhere steady flow cannot change, that is a first role and if I want to change it in a quasi static manner whatever I change something. Then I am actually going through this process, and then I am saying it does not make any more changes, that is what it is really I will come back to good example there later.

(Refer Slide Time: 06:27)



Now if I tell you that there are shocks coming through into a fluid element from two directions, this is one case which I did not consider before, there is a compression wave coming from this side, there is a compression wave coming from this side into one fluid element. This may also happen may be there is a change here, which says compression wave should go here, there is a change here which says compression wave should go here this may happen.

If it ever happens then I am going to say that, because of this the flow property here should in a way change, because of both of this together, this is the centre most fluid element or something. So, I do not want to think about it here, in a similar manner as there is a wall this compression wave comes here, that vanishes into the wall and a fresh wave, start after that and goes this way that is the way. We thought about if it is a wall here, we want to just think about it much more simple, I just say this just crosses through this just crosses through the other direction.

That is a easier way to think about this problem, I have implicitly used it already, when I discussed this situation where there is a point disturbance there is a spherical wave going this way. And there is another point disturbance which will send another spherical wave like this, I have already crossed it several times. I am implicitly assuming it there, but now I am write a stating at explicitly this will help in some situations, in fact I will use this in one of these situations today.

So, the next thing we want to think about is instead of constant area duct I have a let us say a diverging duct, and let us say there is a wave standing typically I am interested in compression waves. So, I am thinking about it is a shock sitting here, it is a very strong set of compression waves together, now I am thinking about flow is going this way, m greater than 1 here, m less than 1 of course, in here.

And now, I going to say somehow suddenly, I am changing this flow field what do we do to make this shock move in a divergence section, this is our nozzle flow problem. Say I want to move my shock more downstream, what can I do I can decrease the pressure here, or I can increase the pressure here p naught, both will change things. What I am really doing is I am actually thinking about p back by p naught decrease, I can either increase the numerator or decrease the denominator both can be done.

I have to push move from this side or pull from this side both will work to move this shock this side, that is the idea, so let us look at both of these cases first let us say I have achieved some study state it is stationary at this location. Suddenly, I am decreasing p b what should happen, if I decrease p b; that means, I created somehow an expansion, suddenly a wall moved away imagine this as big duct.

And suddenly the wall of the duct moved away there is empty space that decrease pressure, which means I sent out an expansion wave into this, whole region those expansion wave. Since, I am talking about one d problem here, I will assume that the expansion wave comes from this way only in the 1 d manner. So, it is coming this way what are these shocks really, I have already talked about it right this is flow is going this way, and the shocks are running up stream, that is the current situation, the set of compression waves running up stream.

Now, if I have this expansion also running this way will it ever go and catch up with this, it will because of the very first rule we put in unsteady gas dynamics. This is a compression wave proceeding in it will go and reach, it will go and reach this. So, what am I eventually telling overall, I am telling this particular set of shocks together plus 1 expansion is equivalent to this shock strength decreasing, it is not as strong as before.

If that is the case what I have essentially done, when I decreased p b I have sent out an expansion wave this way, which will decrease the strength of this shock, and because of that this shock will be thrown out this way. And so, I am going to have this shock moving this way that is one explanation other way of thinking about it, p b I am not changing I will keep that constant, I will decrease this ratio by increasing p naught, this is more tricky to explain it can.

Of course, be explained in one simple way this is the hand bear argument similar to what I just gave, if I increase my p naught I am going to say that the flow can push better, flow has more energy it can push better. And so, the tread mill starts run fast think of it that way and, so the shock will move this side that is one way of thinking about it, but a more logical answer should be I increase the pressure here.

If I increase the pressure somehow, I have created a compression wave that compression wave has to go through this whole thing, I have created some change which was pressure has increased. How is it communicated through the whole flow field by a compression wave, that compression wave comes through this am thinking one d problem. So, it will be a one d compression wave coming through this whole region when a compression wave comes through this way, what should happen it will induce flow velocity this way extra more than what is currently there.

Flow velocity would have changed a little bit that is what I am thinking about, if that has changed a little bit what is overall happening, for a short while I am seeing that this velocity is higher. While this set of compression waves did not see any change from this side this set of compression waves are created by some particular p pressure p b here, that is not changing, but the p naught side has changed.

So, this is not anymore in equilibrium at this location, it moves it just starts to move this side, that is the reason I have to give when I do this it will shift this way. I can of course, give an alternate explanation for if I change the pressure the opposite direction, then the shock will go more upstream induced velocity is now, if it is a expansion fan I am sending through this whole region, then it will pull all the flow the opposite direction.

So, the flow induced will be on towards upstream and, so it will go more upstream shock, if I decrease my p naught, these are simple ways of explaining things. Of course, if I have to go on and look at the exact detail of how this happen, and what is the sequence in which it happen, that is more complex I do not want to go into that much detail in this course really.

Now, I will just tell you one more extra thing, if my shock moved inside here, will it still have a same strength has it was having it here, this is this shock coming from down streams side. Will it have the same strength as it was in location 1 and 2 from 1 it moved to 2, if it happened will this shock have the same strength. Why not we know from study state that it will not because it is a different area different mach number approaching, so the shock strength will be lesser, how will I explain it in this unsteady world, why is it is strength decreasing.

The way to explain it is there is a wall that it is seeing against it, now part of this set of compression waves has now stopped at the wall, it is no more working. They just went and they stopped, it has reached a wall, that is all it matters for it, so lesser compression waves are going through here, which means it is less strong, so it is strength p 2 by p 1 will automatically decreased that is the unsteady way of looking at this things.

If I have the convergent section it will be the opposite, you will suddenly find that the wall is pushing along then things will change the opposite direction, if I have and there is a shock sitting here. And again I am going from 1 to 2, if I do this then here the wall is pushing the fluid this way, I told at the beginning I believe, if I have a nozzle divergent portion I will not have pressure force actual force from this portion.

It will just be negative force negative thrust that is actually given in, so many proportion books, it is a proportion area. I do not want to discuss that too much, but you will find that the wall is pushing the fluid that way, which means it will get a kick in the opposite direction overall. That is what we need to think about that is happening from the pressure chamber here, that is pushed this way while this is being pulled that way, that is what will happen in the flow.

Anyways here the flow is being pushed by the nozzle, this way while the flow is happening this way the nozzle is resisting the flow, and because of that the shock strength will increased. Now, that is the opposite way of thinking about things it is it is this is what is going to change the stability of the shock in divergent versus convergent portions, they will be very different. Now, if you want to think about explaining will the shock be more stable or less stable in here, this is easy to explain just from whatever I talked about in divergent section, in convergent section it is not, so easy.

If I think about why is a shock not stable in convergence section, I need to also take into account if I think about a c d nozzle and the shock is transported through this whole thing, we talked about this in supersonic tunnel starting up problem. Where, you said that the shock in convergent portion it is not stable, it immediately jumps to that side divergent side why is it.

So, the explanation is related to this region in here, the p naught 2 at location 1, when the shock is at 1 p naught two is down stream of shock, what is the pressure versus. If the shock move to 2, then there will be another p naught 2, I will put p naught 2 at location 2, these 2 values, which one will be higher. If I think about it one will have a higher value than 2, if both of them are starting with same p naught 1, this is a higher mach number shock.

So, it will drop more p naught, if I do not have the shock and I have only that then that will drop lesser p naught, which means this value will be higher than this value I am going from 1 to 2 I have protuberated this way. If I protuberate from 1 to 2 I have pushed the shock for some reason up stream, if I protuberate this way, now I am telling that p naught two is lesser.

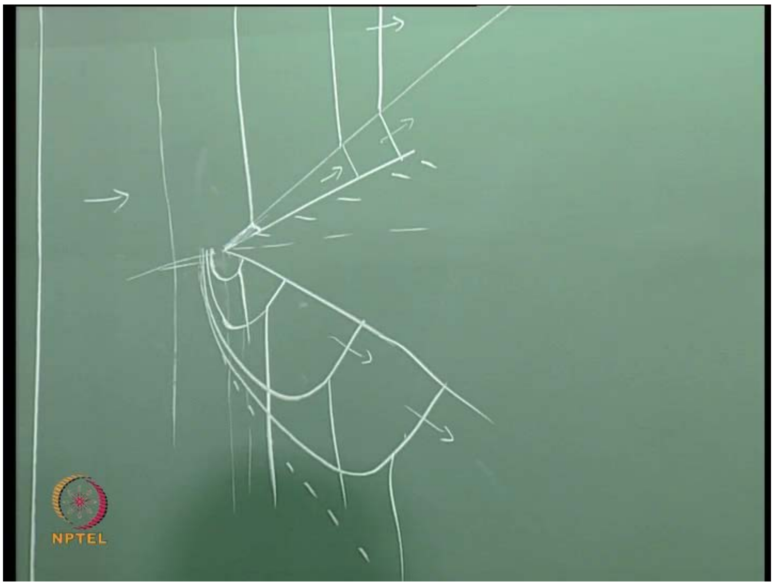
Which means if p naught 2, I will write it down here, p naught 2 is less than p naught 2 at 1, because of this I am going to have lesser mass flow going out through this throat if there is a case the incoming mass flow is still the same. What will happen, now there will be accumulation in this region behind the shock and between the throat and the shock, that region there is accumulation.

What is that mean less mass flow going out more mass flow coming in will cause accumulation, because of that there is going to be a pressure rise. Which actually means that this flow is going in and pressure is rising near the wall, the walls are sending the fresh compression waves this way what will those compression waves do. They will come and catch up with the first compression wave, as usual compression waves leading will always make the other compression waves come and catch up with this.

That compression will come and catch up this shock strength increased, now it can run faster against this flow and it moves more upstream once it goes more upstream. I can go through the same analyses one more time and I will tell that it will go more upstream, I will keep on going it will just boot staph to get out of this whole place it will not sit in a convergent portion. I can give the opposite explanation for if the shock is going from 2 to 1, I will find that mass accumulation will be negative, which means I am sending expansion waves, which will weaken.

The shock which will push the shock more and more that side, in both cases it will be unsteady unstable that is one way of looking at things here. Overall we have discussed a lot of unsteady problems, which are happening in our regular flow fields, I will just discuss one more which you can find pictures of in several books in probably on the net somewhere something like e fluid kinds of site you can see it very easily.

(Refer Slide Time: 19:27)



If I have a wedge flow, and I am saying that I am having a supersonic tunnel just now beginning to have a flow, that is the starting normal shock just now traveling through. How will the flow field develop around this body, till now there was no flow or very low subsonic flow, suddenly there is supersonic flow coming and it is always leading there will be a leading shock that is your starting shock of your tunnel.

So, when that starting shock comes here, this is supersonic this is subsonic, and it goes through when it touches here first what should happen that region, let us say it is less than critical theta. I will draw that on the top side and I will come to more than critical theta on bottom side, if I think about that ideally in steady state condition this must be your shock line. Let us say this is your wall, and this must be your shock line in steady state condition, what you will see will be I call it as if it is a carpet and you are just unrolling the carpet on this board kind of thing.

So, what you will see is this is the edge of your carpet that you are unrolling on it, as it goes through you will find that the flow field develops, this will become your shock and there will be another shock here. It will become something like a lambda fort there if I go more there is your starting shock moved more downstream, you will find that this shock is formed already up to here.

And then there will be a lambda fort going this way if you look at it locally there is a normal shock traveling along this wall. This normal shock is having an angle simply, because the fluid itself is having an angel and it is going to go this way along this one, and similarly if it goes here it goes like this. And this normal shock just keeps traveling this way while the original big normal shock is going to travel the regularly way, this is what you will see as if you are just unrolling the carpet or unrolling the canvas, as it goes along this way.

That is what you will see I will show you a video of that it is very nice to see starting of the flow field, if it happens to be more than critical. What will happen now this is not as easy, because there is subsonic region there will some feedback, anyways I do not want talk about it too much. I will just tell you that when it comes here the very first time, this flow does not know that it should have a stand of distance.

So, it will go and hit it does not know, this shock does not know that the flow here is going to face a wedge that is more than critical angle I am drawing that for the bottom half ideally, I should draw symmetric wedges and talk about it both sides. I will just do separate wedge, which is not really symmetric, what will happen is the very first movement the shock will come here.

After that this will not I will draw the full final envelop this should be my final shock, what will happen now is when the shock is somewhere here. It will start bouncing around it will form a spherical wave like thing from this side, ideally I am drawing only the bottom half of the whole plot. So, it will form a spherical kind of circular wave, which is going partly up stream partly to the side partly along the flow.

All that is happening here and this wave will become perpendicular to that something like this, will start happen and if I go more downstream that is at a longer time will do something more like this. It is going more and more downstream and there is a wave traveling more and more upstream if you noticed, this is the wave which will finally, come and stand at this point.

Ideally if you do the experiment of this unsteady case it will go through this kind of process of course, there is a lot more to study I am just drawing the simplest case. Eventually these waves have gone there and the feedback from the wedge is coming back now, and that wave is coming in and eventually they will come to an equilibrium along this dotted line I have already formed almost this dotted line. And eventually if I go a later time, it will be something more something like this some such flow you will get.

This way I am still having a normal shock running this way, which is telling that the fluid should go along the wall, and here it is coming and resisting this flow this normal shock is coming here, and making sure that the flow is subsonic. In front of the wedge in that region of course, in other regions, it is not really good normal shock it is partly oblique shock. So, it is going to become supersonic after some distance, this whole thing this eventually develops into this dotted line flow, this is what really happens I do not want to discuss more of unsteady phenomena here will just go and look at some videos of unsteady flow field developing itself.

So, I will show you the very first case will be a starting of a nozzle, there is a nozzle up to here, there is a glass wall which is extending fast the nozzle, and then this is the starting shock which is going here. And this region is just a subsonic jet, and here it has not reached the exit yet, but it is going towards exit, is around here it is just going toward the exit, and you already starting to form those shock cell like structures.

There is one more shock forming here, because of this lambda foot reflecting on the wall coming back as expansion crossing, and going to the free boundary bouncing back as a shock that is happening one more round here, I hope to show you the jet boundary very clearly. You can see that whatever we discussed in the jet, where the jet boundary will expand and contract and, so it depending on another it is the oblique shock or expansion at the exit, when this shock goes out it is now outside the nozzle.

It is just about the exit of the nozzle, and after that it is going to start forming only the centre will be a normal shock and the remaining portion will be a oblique shock. We are slowly developing into over expanded nozzle it is just going through that process, I will just accelerate this portion you can actually see some mach waves in here, which way we can use to find the mach number also.

So, you are finding that this these two oblique shocks forming from the exit, this is roughly the exit starting to form oblique shocks, and then as this thing goes through this is the normal shock which I am talking about, as if it is the canvas that is being unrolled. It is just going out and you will start finding that this will form that x like shape here, which will become your over expanded condition which will automatically form.

So, actually you can now start seeing that this is actually glass edge that is not showing you what is happening behind in, but after that if you see oh now the jet boundary is now visible. So, nozzle is currently having a shock somewhere in here it will go past it, so I will show you, so this is a condition where there is a x like thing as crossed this is our over expanded condition, it goes through like this from here.

If you carefully watch this a jet boundary is coming down, and then it is going back out when it is expansion I will pause here, so after this is actually a Schlieren image. So, when it is it is knife edge is set like that such that if it is bright, it is a shock if it is dark it is an expansion this shocks go reflect of coming back as expansion region, which we cannot see in this picture.

And you can actually watch that the boundary is going down and then coming back out like this, and that tells you that the flow velocity vector for the final stream line at least is going to go like this and then it is going back up like this. That is what is happening here that whatever we discussed can be seen here, but I could not go up to a condition, where this will go over expanded.

We have done over expanded it does not go under expanded yet, that is because of limitations in the lab we could not go beyond some pressure, so will show you some other picture. The next one is starting of a tunnel with wedge inside it supersonic tunnel mach two tunnel with a wedge inside, it supersonic tunnel mach two tunnel with a wedge inside it.

This is actually the wedge you can see it sitting here, it is looking inverted because of Schlieren image, again Schlieren is kept such that shock will be seen as bright, this is not the actual shock to be form the actual shock is still upstream. It does not come in yet, we just saw glimpse of it once inside here, actual shock is still sitting here, it is coming in into the view of camera.

It is coming in that is the shock, it has to go pass this whole wedge for us to develop the full flow field currently, it is all unsteady because this is your friction chocking happening here, and that is causing slight supersonic flow. And it is not very steady, can also see some unsteadiness here because of the boundary layer is tripped across this shock, as it goes through those things will all become very steady.

Once this shock crosses the model will find that the flow is very steady on this side, here it is very unsteady it is now see you can see that shock getting developed, as it goes through as it is going through it is going developed. That is the good thing about this flow field, see it till here it is developed after that is not yet fully developed, if I see again from here, this is getting developed from this point, on see the shock is being drawn.

Now, as the shock goes through there was one glitch here, as because this model is flexible model it moves, because of pressure difference across the edge of that plate. That ignore that for this particular video, what you wanted to see is just the shock is getting formed along this line with the wedge. So, go to the next one, where I am showing you full supersonic tunnel miniature version of full supersonic tunnel, now the flow is from right to left in this particular case, and it is currently just coming out of the first nozzle.

This is the steady portion here, straight line portion this is supposed to be your usual test section, and then there is a nozzle second throat going like this somewhere here is the second throat, this location I will just keep the mouse here for some time. This is a second throat location and you are finding that the shock is very unstable in the convergent portion, from here to here is the convergent portion and you are finding that the shock is very unstable.

Will you can see that this oblique shock is formed, where ever that convergent portion is starting it is a linear convergent portion. So, you are getting an oblique shock at that point that is coming through also, and after that you are finding that the shock is going to go un steady in this region for some time. That is the our topic of interest in our lab we study that particular flow of how a shock crosses a second throat, at will ignore that for this course.

After that I just want to show you a case, where I am going from oblique shock to a detach shock, this is the actual experiment for which that model was made this is shadowgraph image. And we are showing you a case where we are starting with this it is a same tunnel, as we talk before the shock was starting that case the model is now inverted, because it is just a shadowgraph in Schlieren.

There is one more optic which will invert the image you are seeing the mach wave here very clearly, because of small cellophane tapes stocks on the nozzle wall, you are seeing these waves coming up with these waves you can find the mach number of the flow also. We found it to be somewhere around 2.17 2.19 kind of numbers, and this top plate is made such that it can move change it is angel, it is currently below critical angel it can go above critical angel that is how this is manage.

So, will just play this video it is just showing you one transition, so currently it there is cam here which operates, which will make the plate go beyond it is critical. So, it is currently a curved shock in front of it of course, you should know that the shock in the shadow graph is dark followed by bright. So, you are seeing this as a shock here this whole region is the shock in this case and you are suddenly seeing that there is the curvature here, which is not the case when it goes back to oblique is this is a actually straight line shock here.

Now, our interest in this problem is to see what angles are coming up along this front tip, is it going to follow the theta beta m curve or not. That is what we are looking for now the remaining things we did set of experiments in the lab for some general unsteady flow phenomena, we did things like I already talked about it little bit in the last class. We took a plank and made it drop on the ground drop on another big plate, and because of this we said there will be a compression wave in front of it even it is very subsonic flow.

I actually measured the velocities to be 6 meter per second, for this plank falling down and we also did a ruler going and hitting a metal plate, and that was giving the loudest sound and we could see good compression waves there. I will show you a case where balloon is pricked by a pin also these kind of videos, which we used to finally, come up with proof that whatever we are talking about in unsteady gas dynamics.

It is all working there is a high pressure region, and the low pressure region if I suddenly contact them this will send out a compression wave. In this direction like that that kind of proof is just of course, fun videos for the people in the lab, I will show you the balloon movie first, because this is the worst case we ever have again, I am having trouble it looks like. So, this is the balloon am holding in hand, and there is the pin this is actually a very tiny balloon.

So, that we can see inside our camera, so I will play it again what you are seeing is the balloon the rubber has gone shrunk here, the hot the high pressure gases are still sitting inside this region and there is this extra wave going out. That wave is going faster than this spherical object like gas sitting here and that is traveling a little slower, so that says there is the compression wave travelling through. In this case actually I wanted to show you the other picture also, that does not look very nice, I will anyway upload that particular part on the web.

Next one I am showing you is the plank hopefully this will at least show something, so here is the plate I will pause it for a minute, this is the plate on to which the plank is falling it is inverted image gravity is somewhere up there. So, if I look at this is the plank that is coming towards that plate gravity is upside, so now, if I plate you are seeing Schlieren such that shock will be seen as dark region.

We have arranged the knife edge such that shock will be dark region, now I paused watch this line forming here this is actually a dark line in the reasonably white background. There that actually shows that there is a shock happening in that region, ideally I should be looking for an expansion in this region, because this is pulling the flow behind it. There should be an expansion in this region I was looking for it, I could not figure it out very well may be I will do more careful experiments next round, but there is more fun stuff happening, when we go very close to it.

So, I will play little more, somewhere here if you noticed till this point there was a shock I will go two steps back, follow the shock there was a shock and suddenly the shock is somewhere here. Shock is gone out it has found, that when this reflects half of that wall those two shocks came together, and form this nice wall shock that is moving very, very fast out very fast. And then the reaming flow is a jet flow from inside this cavity there is high pressure gas inside here, and that is coming out into atmospheric, so there is a jet flowing here there is just a jet forming there.

That is what is going in there the shock is gone, and then the jet flow is going behind it you can also see some nice vertices happening in here behind the shock, I will just play the last bit a little more. Now, if you notice there is one more vertex coming here that is what I wanted to show you, which actually proves that there is a flow from this side which is being dragged in by this body.

Notice here, after the plank hits this flow just oozes over this, and forms this nice vertex rotating here, and you can see dark and bright region which says that it is a dip and increase in pressure in that region. So, it is actually a vertex sitting in that region, now the most interesting picture with that I will stop actually I wanted to show you this video first let it.

So, think of this ruler coming in, and it is going to hit that metal plate and has it is coming in till here, we do not see much happening watch somewhere in this region, there will be a small change in intensity, when the plate hits. It is almost about to hit, now see that there was some change in intensity, and then there is following jet like flow field, which is similar to the plank hitting thing now it is not very clear in this.

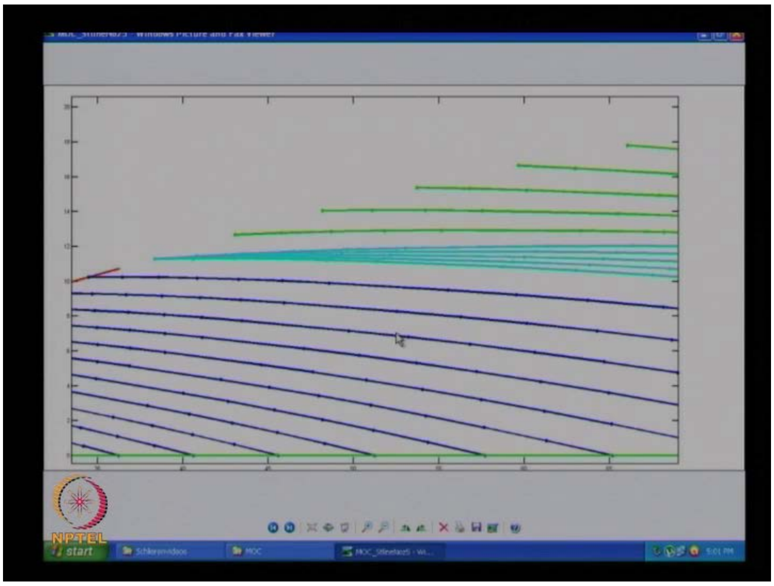
So, what I did was I took one of the where this is no flow happening, that is this ruler is out of this image, I took that as background, and I subtracted that background from all the images, I will show you that corrected version. Now, which shows you a lot of details, here this is where the ruler is it is all dark, now it will suddenly become very bright and this is where your plate is. And it is going towards it somewhere around here you can start seeing some compression waves here, compressions are seen bright in this particular Schlieren.

This is started compression in this region where it is very, very small gap between the metal plate and the ruler goes a little more, and the compression wave is just travelling around it, is a ruler which is just one and a half inch wide. So, there is compression waves that is escaping on the sides of the ruler also, and there is a compression wave that is coming forward also. Now, watch that compression wave it will this is what I wanted to show you is a big shock structure formed at the front, this is what you will hear as a loud sound, when a ruler hits a metal plate.

If it hits very nicely, if it hits at an angle, you would not get that and the remaining things whatever ruler rotating vertices, you are seeing that coming up here, because they said jet like flow field, which comes and opens that is happening in this region. So, this is a shock that is formed in the front of it, I will upload all of these videos anyway and you can see that the vertices rotating slowly the shock has gone well fast. This is the full flow field this is what I wanted to show you guys in here, I told you I will show you some MOC pictures.

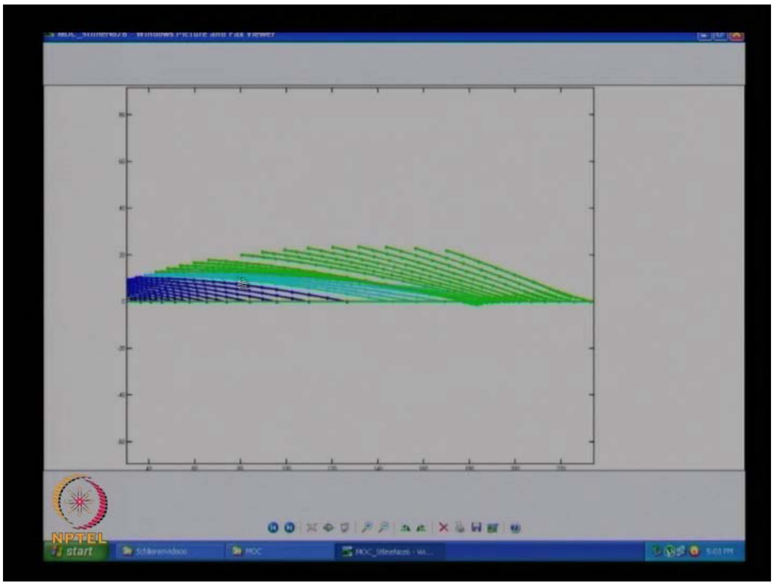
So, I will go back and show you whatever I was showing before, I will open that folder, so we were discussing this how to create this we already discuss this, and we were looking at this how different patches can be created. This is right running characteristic, this is left running characteristic calculation etcetera, now I told you I will calculate more and go for the free boundary etcetera and this region. And this is a very complicated expansion case I picked a simpler expansion from exit mach number of 4, I went to 4.2 just the very small expansion, I did that case after this these picture you have seen already, this is new.

(Refer Slide Time: 41:38)



So, the expansion is very small from 4 exit mach number it is going to a pressure such that the mach number will be 4.2 just that, when you do that you are seeing that there is a thin expansion fan. And this characteristic that is going through here is going to the pressure boundary, forming a pressure boundary point from there it is coming back down this way. That is easy to see and like that every characteristic is going and bouncing off as a pressure boundary and it is coming back, now I want to show you the next interesting phenomena here.

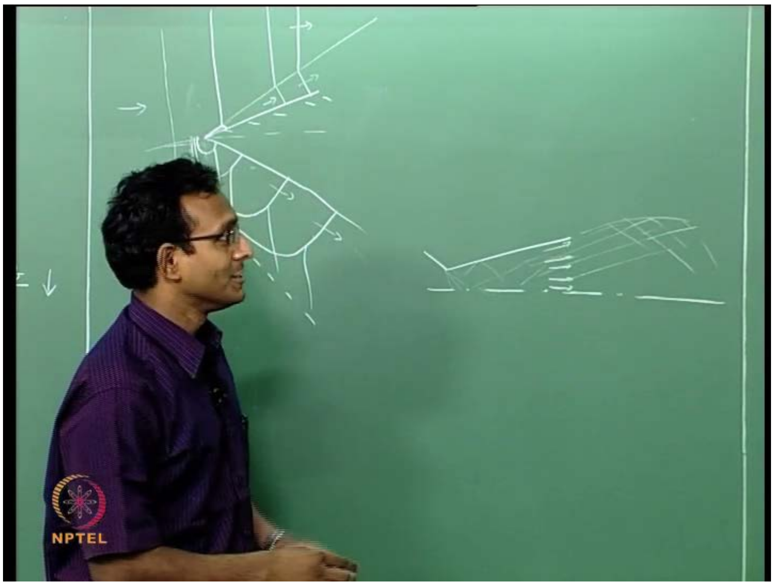
(Refer Slide Time: 42:11)



This I have to explain it to you little bit, you are seeing that the set of compression waves coming from there from the pressure boundary, you can see that I am showing only the nozzle exit from here, and then expansion wave is shown in saint color light blue. And then the green is characteristic coming from the pressure boundary point, you are seeing that the pressure boundary or the jet boundary itself is turning downward.

This is the characteristic of when an expansion fan goes and hits a pressure boundary, it will come back as a shock. That is what will happen in a jet case, but currently we are having expansion fan going this way it has not reflected of the wall, of the axis and gone back that side. And then before that we are having this why is that lets go to the board, I will just talk about this extra thing.

(Refer Slide Time: 43:05)



This is related to what type of nozzle I have actually used, I used the straight line nozzle, which means I am going to have flow field that is like this, if you look at this the flow field is an expanding flow field. It is already coming from here expanding, expanding, expanding, which means I have a set of expansion waves going this way always, these characteristics that are coming out of here are going to be diverging slowly. Because of that, these expansion fan which is actually created from somewhere well ahead, most likely created from this point, this set of expansions have bounced twice.

And it is coming out like this, now when it comes out this expansion meets a pressure boundary, whatever we talked about before will be applied. That expansion will now become compression waves, they are going to converge as they going they will all converge, which is why this is happening, now will go back to the board if screen. If we look at here I am seeing that this set of characteristic lines are crossing each other, this is what I was talking about, if I do not think about there should be a shock, and I just calculated I will find that this crossing will happen.

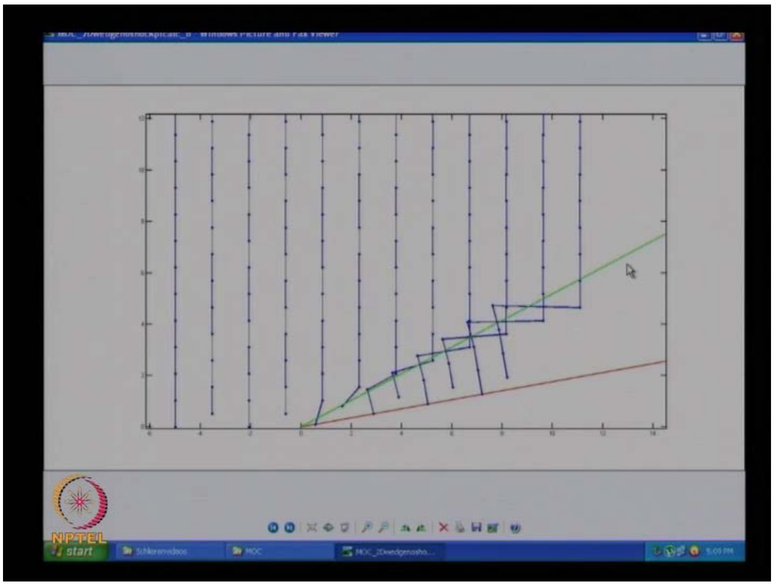
I will go and look at it in little more detail in there, you are seeing that these lines are crossing, and one more thing I want to show you, this crossing is the downstream characteristic is going more upstream, that is what is happening here. You can see that it is crossing even the blue line, it has crossed the downstream lines have crossed the blue line also.

So, I actually means that I have to replace this whole region with one shock somewhere here, that is why straight line nozzles are not used in rocket, because it will have a end shock like this, is why they want a exit calculated very well with method of characteristic. One more interesting thing to see is it is going below the axis also, these are interior points, axis points are still on the axis you will find the characteristics are coming down, and then going back up that will be seen in the next picture.

To see here, I was seeing that particular lines characteristic changing, right now we will look at this particular line we will just go along this line, what you are finding here is there is a kink here also. It will go down here go back up and then go here, that is again another wrinkling of the cloth, so what we are finding is here they are crossing downstream is crossing upstream this way going towards the axis.

And here downstream is crossing upstream in the left running characteristic, which we have not drawn really, if we draw that, we will find that the downstream is crossing upstream. That is why you are finding that these points are coming here, and then the more downstream point here should have been here if there is no shock. That because of shock the next point happens to be here, and then it follows the axis up to there that is happening here, if you see such features you should know that you should expect a shock in your flow in that situation that is the case there.

(Refer Slide Time: 46:19)



I also told you I will show you a case, where I will calculate it as if I am just marching the initial line forward, we always showed you only marching right characteristic or left characteristic. Now, we are looking at I am having initial lines given here this is a external flow I am having a flow parallel to this line, and I have a slopping wall in this case this is the external flow condition.

If I do this calculation I am just marching taking this point and this point putting inertial point here, like that I am going this way what should I do at that corner from there. What I did was I just put a pressure boundary point there, that is a easiest way to do it or else what you have to do is go far away from this body. So, that there is no effect there I can put the free stream conditions in here, and come from there and I am giving a lot of initial boundary conditions, there can also be done that way.

So, what you are seeing is actually the right running characteristic is going along this line, if you notice similarly left running characteristics are going along this line set of points going along like this. But, what we are showing is advancing the initial line forward step by step, if I go like this you see the number of points will change it will increase and decrease and increase and decrease I have not shown the other edge here.

I wanted to show you this change here, if you look at the very first characteristic that is touching the wall, I just have to put a wall point in here, it just comes out to be here nothing great wall point is going from here to here. That characteristic goes and meets the wall and puts a point there, and if you look at the next set of points, next point also does not show it very clearly.

But, after that if you look at it is going behind the previous line, which actually says that there should be a shock somewhere sitting here, if I follow one of the right characteristics say I will pick this one. If it goes like this going, going, going, here the next line is here, and then one after that is here coming back up downstream point is more upstream now. And then it is going to next point that is what is happening here, and I am calculated the immediate next point here if you calculate that will go towards wall.

Now, I just wanted to do one more thing, I super imposed the theoretical shock on top of this picture, just to see how it looks, and it looks something like this, so if I had done the shock point calculations, I should have replaced this region. This whole region where characteristic measures wrinkle, that whole region should be replaced with a shock like this, that is what should have happened. So, that brings us to the end of our course hopefully I will put up some more problems, and exercises on the web with some solutions or possible answers to whatever questions.

So, that will give you better insight and you can go and work out those problems and get compared the solutions, I hope I have given you enough insight into the gas dynamics field, as such what we did not do till now is if the c p by c v ratio changes along the flow. While the flow is happening the c p by c v gamma ratio itself is changing, if gamma changes, then I have to take into account the local gamma and calculate everything based on that.

That can be done even in method of characteristics every point, we have to just tell that interior point loop or whatever loop you have tell that I have to send in a gamma along with it. Then I can take it such that it will work for each individual gamma at that local location, how will I find the gamma variation that needs a lot of classes. So, I do not want to discuss that here, that is beyond the scope of simple gas dynamics course, overall you should be able explain external flows, and internal flows, high speed flows.

You should appreciate the difference between incompressible limit and regular flow field, I did not go to hyper sonic limit, which is again simplifying things I talked about it a little bit in isotropic flows. Where we said most of the curves asymptote to simple value, when mach number is more than 7 or 8, there is a hypersonic limit there is a incompressible limit most of the flow fields in nature are all in the compressible range.

You already now know that in unsteady flow everything is compressible, this is the main idea I wanted to get through in unsteady gas dynamics course, where I will just tell any flow field. Even if it is point one meter per second, if it is changing it is velocity or pressure it will send out waves from one point to every point around, that is up to infinity if the waves travel the wave is may lose it is strength.

If it is expanding if it is the spherical wave expanding it lose it is strength, but it will still induce the change, it will induce a lesser change, but it will still induce some change. Whatever change suppose to be done, if it has to increase velocity of the fluid it will increase a little lesser has it goes out away from the, but it will definitely change. So, somebody ask you next time, if I move my hand this way, will I send a compression wave you should say, yes after this course typically if I move it in subsonic conditions all the standard gas dynamics books are all written for steady state.

Where, they will all say, yes if you are moving subsonic there is no shock, but in here we will tell we are sending a compression wave, even if it is moving at 1 meter per second. We showed you movies of 6 meter per second movement of ruler, so you should know that it is possible compressible flows are possible, even if it is mach number far less than 1. If there is any unsteady flow it is always compressible flow that is a way to think about it hope, I will I have given you clear idea of whatever is happening, I will end with this point.

Thank you for listening.