Gas dynamics: Fundamentals And Applications
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Lecture 59
Shock Boundary Layer Interaction- II

So, we are discussing shock wave boundary layer interactions which become important in high Mach number flows where you have both the shocks as well as Boundary layers close to the wall. In the previous class we had a brief introduction to what are Boundary layers what are how do they behave what are their equations in a qualitative sense. We looked at the flow of the phenomena of flow separation which is important in the context of Boundary layers and it increases drag significantly and we looked at compressible boundary layers.

Now we look at how these facts these various observations that we made in the last class how they affect flow in high Mach numbers when you have shock waves also.

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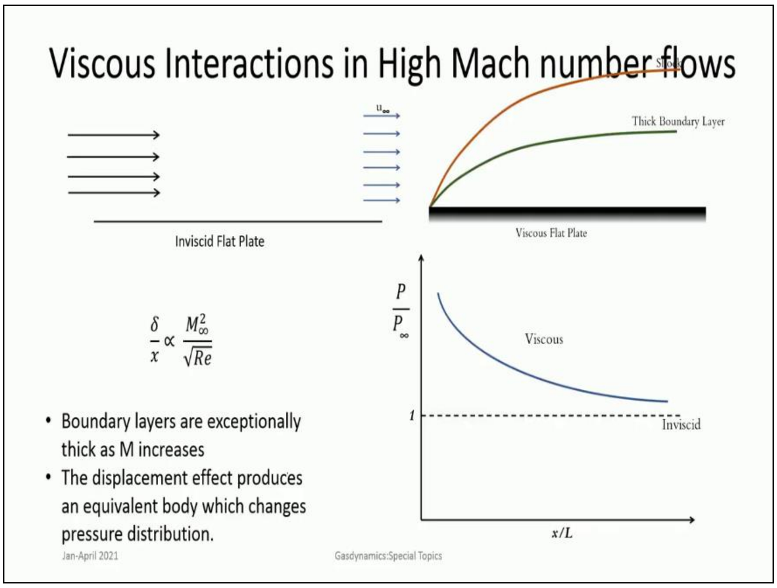

The first concept is that of the boundary layer we know that it increases rapidly with Mach number. So, here if you consider this picture this is of a flat plate and if it is an inviscid flow and a supersonic flow in supersonic or high Mach number flow inviscid in nature. Then the flow is not affected at all it just flows over everything is constant pressure is also constant.

But in real flows you have viscosity, and the consequence of viscosity is a boundary layer develops. So, here is a boundary layer that has developed, and the boundary layer thickness is relatively significant in high Mach numbers. We also know that the boundary layer produces a velocity v infinity or sorry v which actually deflects the streamlines outward and as a consequence the thickness or the boundary layer grows.

So, that means the flow coming from uniform flow coming from outside is getting deflected and this is a supersonic flow. So, any deflection in supersonic flow should produce the deflection which is towards the flow or flow turning into itself it should produce a shock. Therefore, we find that in viscous flows when you have viscous flows or in real flows where there are boundary layer shocks are always produced because the really thick boundary layer produces significant displacement.

So, the outer revision flow is seeing a certain displaced flow or an equivalent kind of a body which changes really the pressure distribution that is felt on a flat plate. Ideally if you did not have the boundary layer if it was completely measured then you should have the pressure distribution as same that is what one. But because of the boundary layer and the viscous effects there is a different pressure distribution that is felt.

So, now we see that there is an interaction of the thick boundary layer with the inviscid flow that is outer which is termed as viscous interaction and viscous interactions change the pressure field or the pressure over the body. So, when what we are interested really is to find pressure over bodies.

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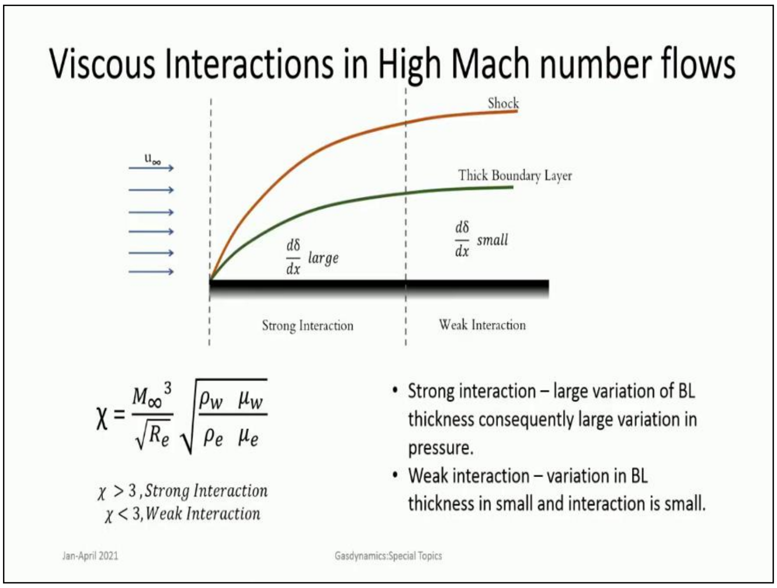

What we typically saw in general what is done is we consider an inviscid flow, and we find the pressure distribution from the inviscid flow. Impose that pressure distribution onto the boundary layer where across the boundary layer there is no change in pressure. But what we find here is the presence of the boundary layer itself changes the inviscid flow in a certain way. This change is large in this region where the change in boundary layer wherever change in boundary layer thickness is very large.

Then the interaction with the inviscid flow is very large we call that as a strong interaction. A viscous interaction parameter chi is defined which goes $\chi = \frac{{M_\infty}^3}{\sqrt{R_e}} \sqrt{\frac{\rho_w}{\rho_e} \frac{\mu_w}{\mu_e}}$. So, by evaluating this parameter chi we can find out whether the interaction is strong or weak.

In weak interactions the change in boundary layer thickness is relatively small therefore the effect on pressure is also relatively small. So, strong interactions are close to the leading edges where you have a large change in the boundary layer thickness. This is one kind of an interaction which happens in high number flows which is due to viscous effects and thick boundary layers.

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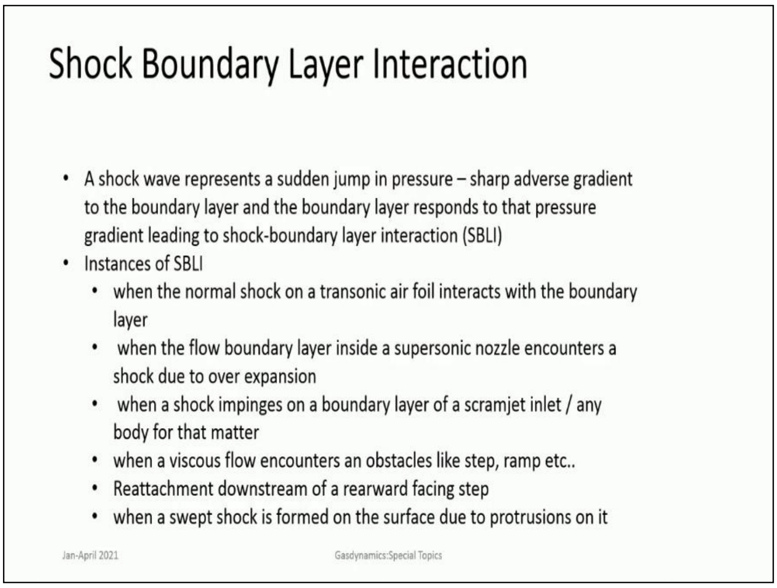

The other kind of interaction that occurs is the interaction of a shock wave with the boundary layer. A shock wave is a sudden jump of pressure and pressure increases across a shock wave that means there is a sudden increase and that represents a very sharp dp by dx. So, dp by dx is greater than 0 it is not only greater than 0 it is very sharp it is a sudden increase in pressure. We know that the boundary layer responds to adverse pressure gradients.

Boundary layer thickness in general increases in advanced pressure gradients and the separation phenomena also occur in adverse pressure gradients. So, what happens when there is a shock wave boundary layer interaction? So, let us look at that there are several instances where we can find shockwave boundary layer interactions. They appear on Airfoils or wings when they travel in the transonic regime.

So, that is the case. So, there are several instances in which shockwave boundary layer interactions can be found. Whenever we consider an Airfoil in transonic flow this is not very difficult any normal airliner trans goes around Mach point 8 or so, which is in the transonic regime. And very early on in the classes we had looked at a few images of Airfoils in transonic flow and we saw that there is a pocket of supersonic flow and so, a supersonic flow pocket develops and then finally is terminated by a nearly normal shock.

So, now this shock impinges on the wall of the Airfoil and always there is a boundary layer that is there over the wall and therefore there occurs a shock wave boundary layer interaction over there. Similarly, if you consider any flow for that aspect where there is supersonic flow and there are walls for example nozzle flows there are Boundary layers on the walls of the nozzle.

If the nozzle operates in off design conditions especially over expanded conditions shock waves forms with maybe near the nozzle exit. Then there is an interaction of boundary layer with the Boundary layers shocks and Boundary layers at nozzle. Then any say a shock generator impacting giving rise to shocks which impact on any surface over which there is a boundary layer this leads to shock boundary layer interactions is typically in say intakes and so on.

If the protrusions they are in supersonic flow steps both forward facing steps there is a shock that develops boundary layer is there and there is shock wave boundary layer interactions. So, there is any body in supersonic flow for that matter you can expect there will be some form of shockwave interact shockwave boundary layer interaction.

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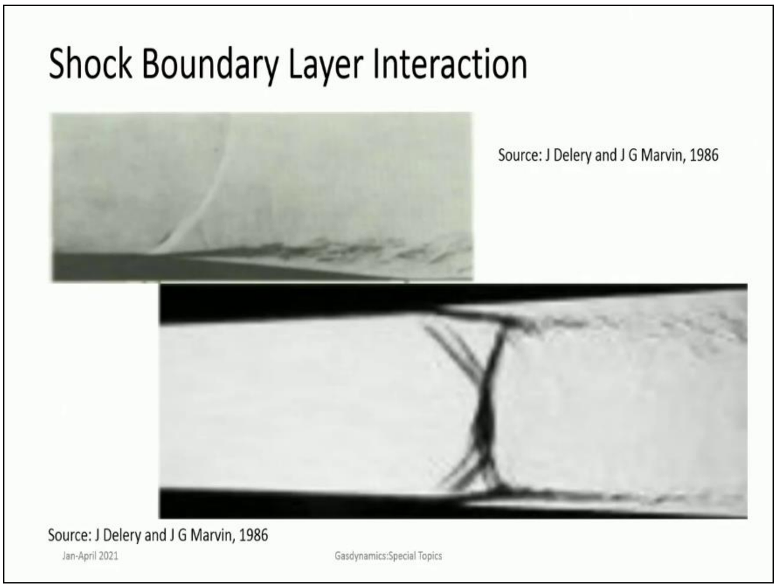

So, here are some images taken from different literatures available on this topic. For example, this shows a near normal shock which is what like what is found on Airfoils in transonic regime you have a shock here and the shock has interacted with the boundary layer and the car as a consequence there is a separation of the boundary layer over here. Similarly, this is a flow in a variable area duct which can be a nozzle also and here there is a shock that has occurred within the duct.

What we normally expect or when we talk about rocks in ducts which we have done in this class we said that there is a possibility that a shock can occur. We considered a normal shock in this case and we did lot of calculations assuming uniform flows before and after the shock. But now if we consider a real picture of flow within the duct and a shock that develops in the duct then the shock interacts with the boundary layer.

And the boundary layer is affected by the shock because of which the shock structure itself undergoes a change here what we find is a shock which is more having a kind of you know a lambda kind of structure here. A y shape or a lambda shape structure while at the centre line it is normal. So, you see that whatever pictures or ideas that we had they are models of real flows.

In real flows where there are Boundary layers and viscous effect is the ball and when there is a shock. Then the phenomena of shock wave boundary layer interaction become important it causes important changes to the flow field and we have to then come and analyse them more closely. Now you can see here also another interesting fact that you have the shock-shock interactions that we had discussed in the previous class previous classes.

So, in when you have such interactions with the shock and boundary layer you not only have shock wave body layer interactions you can also have shock-shock interactions because of changes to the shock structure itself.

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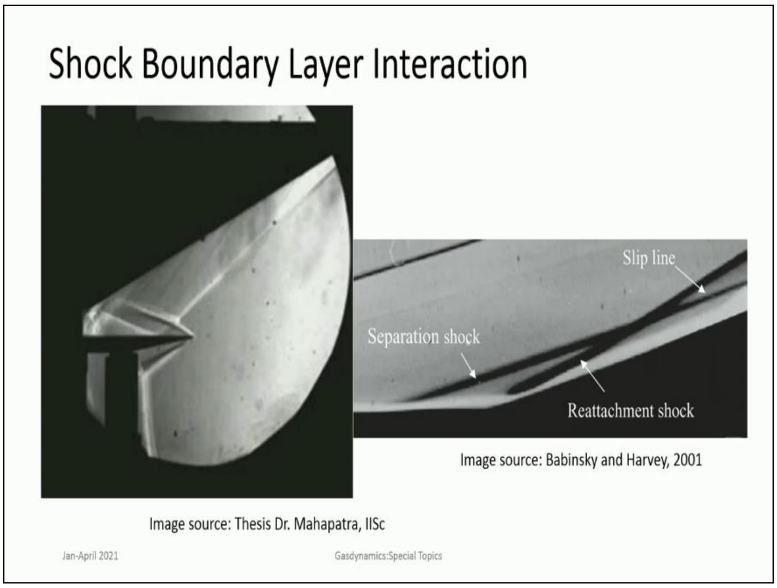

Some more pictures were that will emphasize the importance of the shock wave boundary layer interactions here you have a shock from the four body it is a typical inlet this image was taken in laboratory for hypersonic and shock wave research in Indian Institute of Science. So, here you have a shock wave, and this shock wave now goes and impinges on a cow which is typical this kind of geometry is typical of intakes in high-speed flows in scramjet kind of intakes.

Here you find that this interacts this shock after all the shock interactions interact with the boundary layer on this plate. So, in such intakes this problem of shockwave boundary layer interaction is important. Then you have the corner flows always you can have in many of these flight vehicles, or you can have flows of this kind where you have a corner. Then at the corner you have an incoming border layer you have a free stream.

They are getting turned and there is an interaction of the boundary layer and the ramp produces a shock the turn of the supersonic flow produces a shock. And this shock then interacts with the boundary layer and therefore a shock point layer interaction occurs here. What we normally expect is that there is a shock attached shock over here this is what is normally expected.

But now because of boundary layer the shock structure that is formed is completely different from what we had expected from an inviscid case.

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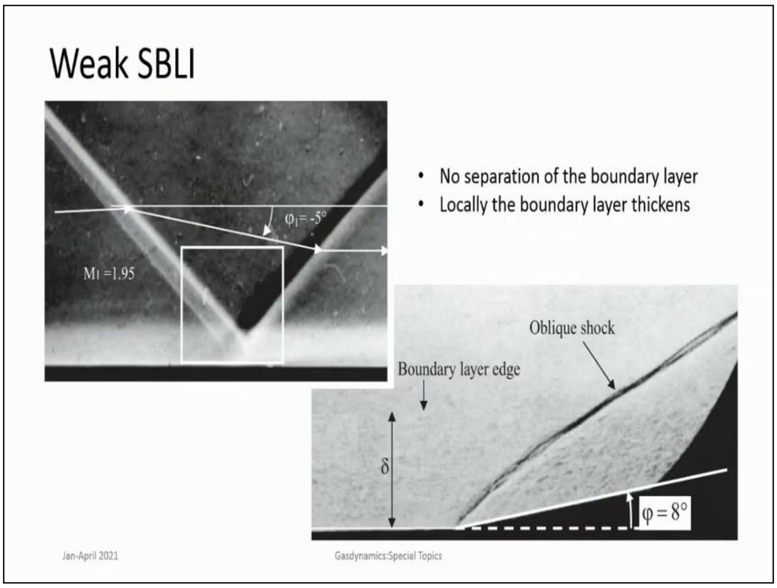

So let us look at. So, these shock point layer interactions the physical flow features they can be classified into weak interactions and strong interactions. Weak interactions when weak interactions happen there are no flow separation of the boundary layer at the boundary layer. So, but boundary layer responds to the increase in pressure. So, there is an adverse pressure gradient that is imposed on the boundary layer due to the shock.

We know that whenever there is an adverse pressure gradient the boundary layer thickens. So, the in weak shock wave bond layer interactions there is a thickening of the boundary layer. But separation does not take place case this is a case of an impinging shock from a shock generator a shock is coming on to the wall boundary layer here. And this shock is relatively weak consequently the interaction is also weak and it just locally it changes or increases the boundary layer thickness.

But the flow features otherwise are relatively they are the same what we would expect when we do not, I mean the qualitative aspects of the flow features are similar to a shock reflection. Similarly for the case of a corner flow over here that is what we expect is that there is a shock along this an attached shock at the corner this is what is expected. You can see there is an attach shock at the corner.

But in the initial part there is a slight curvature this is due to the boundary layer viscous interaction. This is the boundary layer edge. So, you see that the boundary layer edge is much thicker and inside the boundary layer you have a non-uniform flow it can be supersonic also consequently the shock actually is also curved. Then later it develops an oblique shock. But here again it is a weak interaction here there is no flow separation involved.

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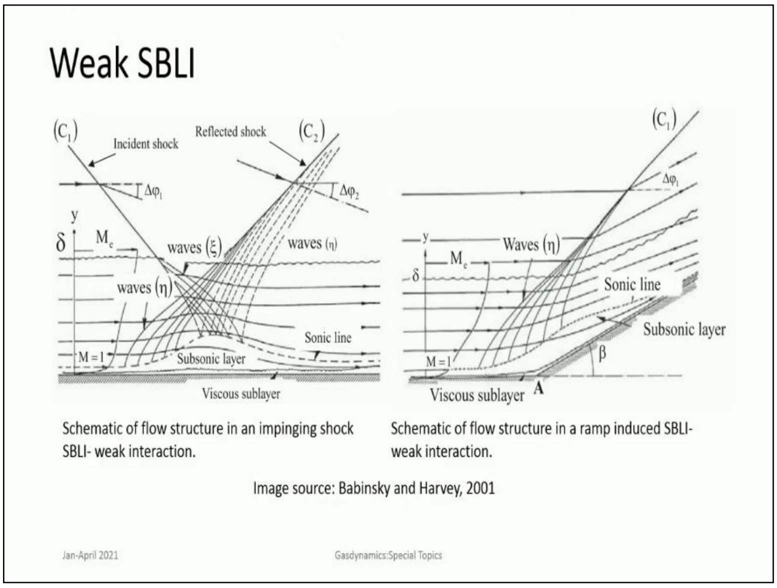

So, a weak shockwave bonded layers does not involve flow separation and it changes the local boundary layer characteristics it may slightly thicken it. But otherwise, the qualitative aspect of the flow features they remain are the shock waves and they remain the same. So, this is the schematic for an impinging shock in weak shockwave bond layer interaction domain.

One must remember that within the boundary layer the flow is non-uniform that is why you have a series of waves that are produced, and your shock curves that is because of the non-uniformity. This change in the structure of the boundary layer can produce certain waves. They can be compression waves that can just coalesce together to form a shock.

The qualitative aspects of these waves and shock waves are similar in the case of these weak shockwave bond layer interactions.

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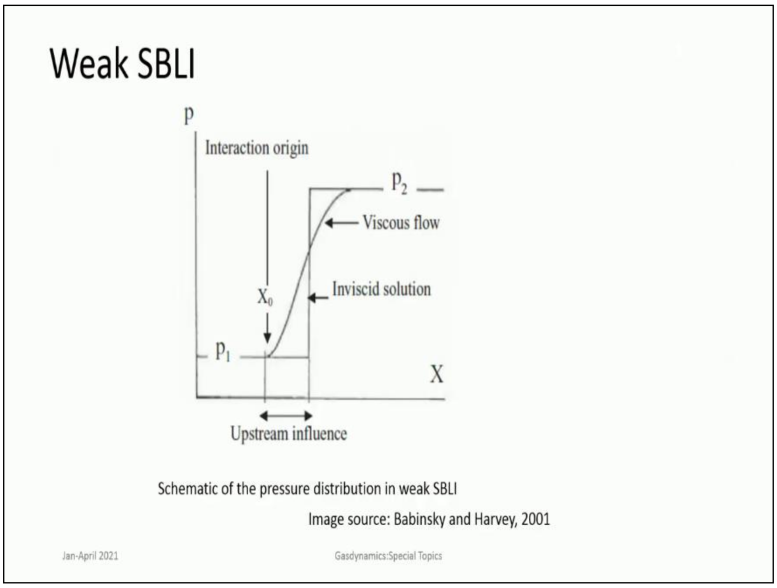

Key highlight here is there is no flow separation. So, what we expected was that in an invisible solution the shock will produce a sudden jump of pressure. But really when there is a boundary layer what happens is that there is a more gradual increase of pressure to pressures after the shock. This gradual increase at the wall is due to the boundary layer interaction and we see that there is a certain amount of upstream influence.

That is if we had considered that an inviscid case it might have interacted at this point on the on the wall. But now the pressure increase happens much upstream compared to this point. So, there is an upstream influence due to the boundary layer where you can have subsonic regions very close to the wall. So, the flow can be subsonic very close to the wall and there can be a there is a line which separates the subsonic and supersonic parts which is the sonic line and that is depicted over here.

The subsonic portion can communicate upstream and cause upstream influence. So, the rise in pressure is more gradual because of boundary layer.

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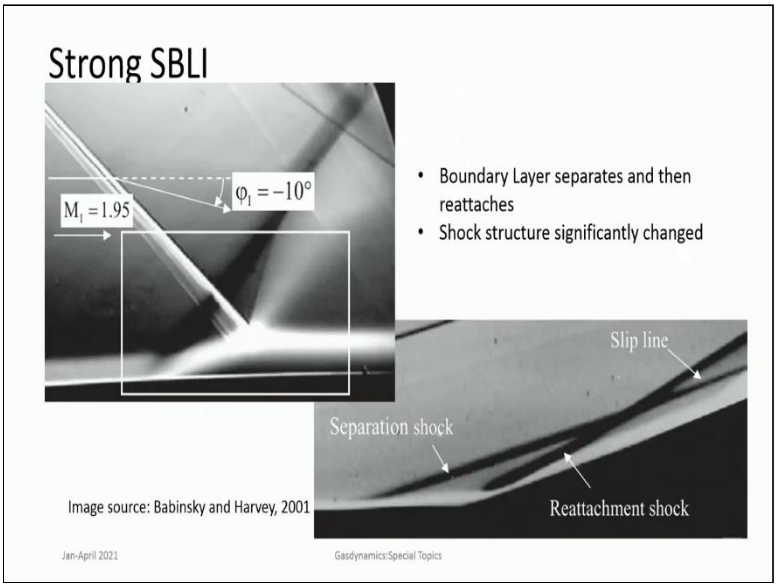

Now we come through the case when boundary layer thickness is boundary layer interaction is strong. In case of strong shockwave boundary layer interactions, the boundary layer separates it may reattach the shock structure is significantly changed its quite different from what we expect in the case of an inviscid flow structure. These are the cases for an impinging shock. So, you see here that the boundary layer just simply separates.

Similarly, this is the case for a corner flow where there is separation. A separation shock is found much ahead of the corner and a reattachment shock is also formed.

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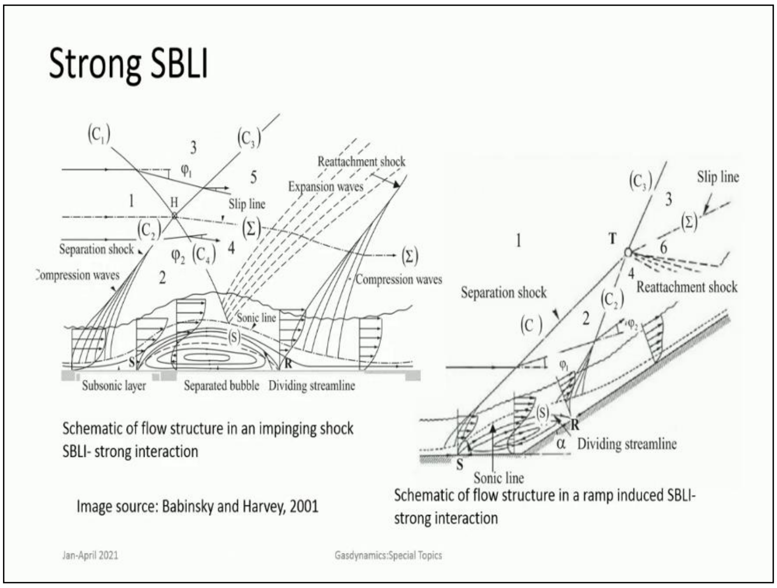

So, let us look at the flow features in such strong shock wave boundary layer interactions. So, here what happens is basically a separation happens. So, flow field is separated here. So, because of this separation the streamlines actually turn they turn towards the flow as a consequence a shock is formed much ahead of the interaction point and with the wall. So, that is the separation shock which is due to the separation which is much upstream of what would have been the inviscid interaction point.

It not only separates it later it can reattach when it reattaches so, you see the nature here it separates. Then it increases in thickness so if you look at the outer flow first is turned into itself it is like a bump. Then after that it turned away from itself when it is turned away from the Supersonic flow it produces expansion fans and. Then Mach number increases here Mach number increases. But then again you have a wall it cannot turn anymore therefore you get a reattachment and therefore you get a consequence you get a shock again.

So, that is the reattachment shock here and you have slip lines and various other features that occur. So, this separation shock can interact with the incoming shock that is the impinging shock and produce shock-shock interactions. So, you see now that this picture is much more complex compared to a simple reflection of the wall. If there is a boundary layer and the shock boundary layer interaction is strong. Then it can change the flow structure significantly.

Similarly for a corner flow now in the corner flow you the boundary layer separates here. So, you have a separation shock forming much ahead of the corner. So, there is much ahead upstream a point a separation shock is formed. After separation, the flow reattaches similarly a reattachment shock is formed, and Shock-Shock interactions occur due to these two shocks.

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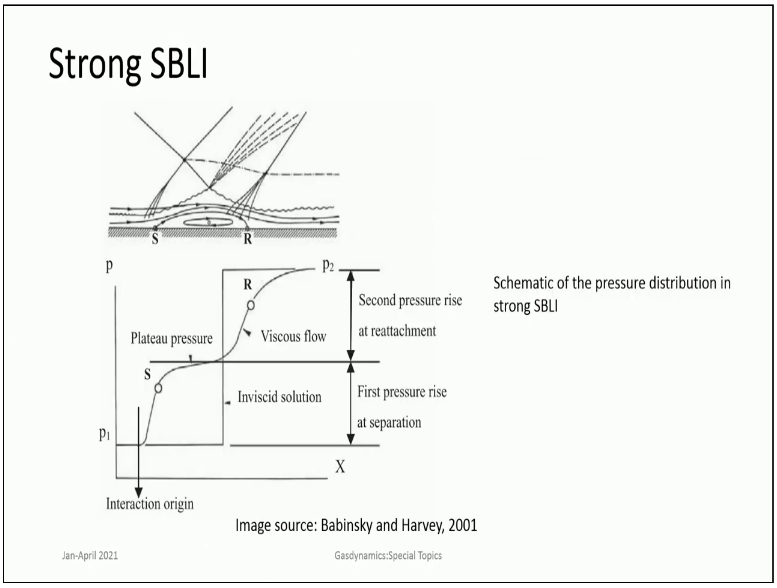

So, we find that when there are strong shockwave boundary layer interactions there is significant change in the flow field. So, you if you look at the pressure profile it is somewhat different you find first there is an increase in pressure this is due to separation shock. Then there is a plateau in pressure in the region over this region where is the separation zone.

There is a plateau region and then again, the pressure increases due to reattachment shock and finally it reaches P_2. So, in strong shockwave boundary layer interactions you have a pressure profile which is of this kind where there is a plateau pressure also.

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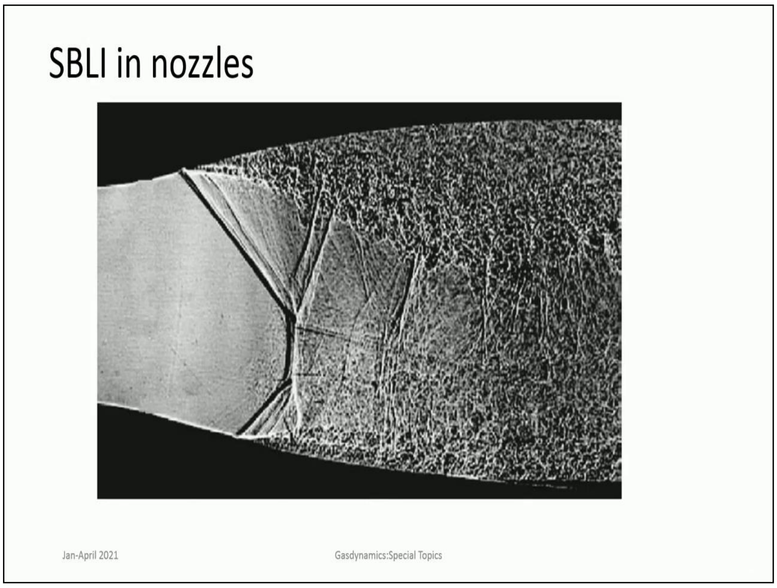

So, the key idea that it needs to be conveyed here is that in real flaws there is always a boundary layer. Whenever there are shocks in supersonic flows or high Mach number flows and there is a boundary layer there is always shock boundary layer interactions and the flow structures that develop because of shock bond layer interactions are somewhat different from the typical picture that we get from initial studies or initial discussions in gas dynamics.

So, this should always be borne in mind that if you look at nozzles, we discussed shocks in nozzles we said that it is like a normal shock and if we capture the flow through an actual Schlieren for example what is shown here. We find that there is a lot of shocks they are completely different they flow can be unsteady also. But there is a normal shock at the at a certain location as well.

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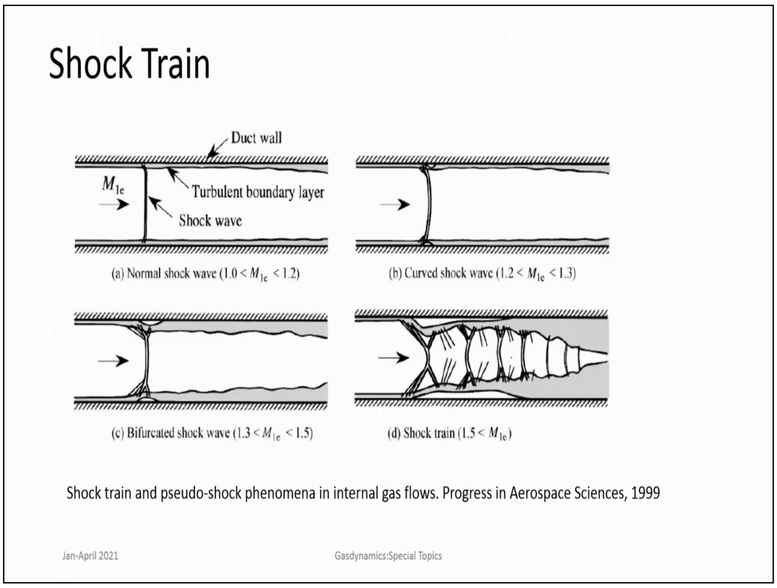

Now let us look at shock waves in ducts also if you consider a uniform duct. Then the there is a boundary layer along the duct wall also. So, if there is a shock wave here in the duct and the shock is very weak. Then you produce weak shockwave boundary layer interactions, and we can say the shock wave is nearly normal. But this is at very low Mach numbers as in Mach number is increased it starts affecting the boundary layer it can produce a local change in boundary layer producing slightly non uniform flows.

Therefore, the shock can become curved. Then the point can be that the shock can produce a lambda kind structure which is of this kind. But there is only one shocks here this is for a slightly higher Mach number. But for relatively high Mach numbers what really happens is there is a boundary layer separation due to shock interaction. But now there is a complex flow features that are developed because the shock the flow separates.

Then the flow separated flow undergoes a series of changes where you can almost consider them as alternate convergent divergent sections therefore you get many, many shocks before it becomes subsonic. So, what you get is a series of shocks known as shock train. So, in high Mach number flows in ducts and where there are shocks you get a shock train due to shock boundary layer interaction. It is not a single shock.

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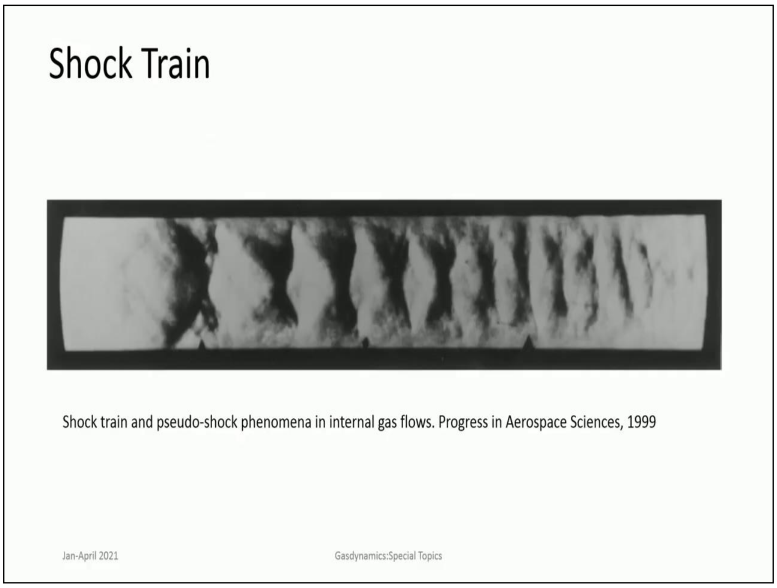

That can be seen this is an actual picture of a shock train in a duct um. So, you can see there are several shocks are not just one shock. So, 1, 2, 3, 4 and so on. so, each of them is a shock after each shock the flow again accelerates. Then it again produces a shock and. So, on and this is a consequence of the interaction of the shocks with the boundary layer and corresponding non uniform flow that is produced.

So, these pictures have been given here to sort of bring about the idea that real flows as they happen in devices like nozzles, diffusers or ducts actually involve both the inviscid effects as well as the viscous interactions. And boundary layer and shock may interact producing significant changes to the flow. But whatever we have discussed earlier on are very good models of the flow within ducts.

So, it is useful to understand how flow happens with inducts and how are shock waves formed and so on but if one starts going into details of the flow in ducts. Then one must consider the additional complexities produced due to shocks, boundary layers, shear layers and their interactions. So, this was a slight introduction to flows in real devices in practical applications. With this we have covered almost all topics in what we had planned. So, with this I close this lecture.