Gasdynamics: Fundamentals And Applications
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Lecture 57
Edney Shock Interaction

So, we are looking at certain special topics in Compressible flows especially in high Mach number flows and we had discussed about Hypersonic flow in the previous lectures. Now we come to another aspect which is called Shock interactions. We have discussed about Oblique shocks, their reflections from walls.

But if you consider a complex body shaped body in Hypersonic flow it will have many features about it.

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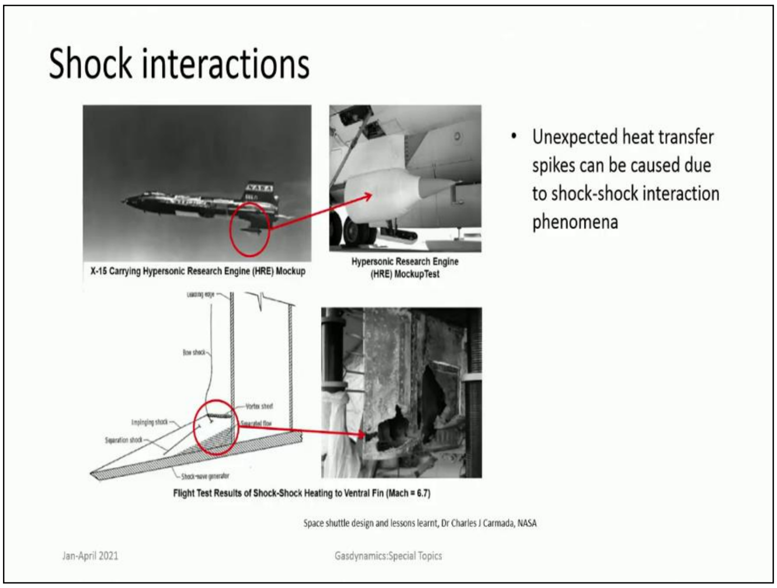

For example, this is an example that has been given due to much earlier during the time when Hypersonic flows were being evaluated. This is an X51 vehicle carrying an experimental setup for hypersonic research. So, you see that this vehicle goes at very high Mach numbers X15. Then but it has also many protrusions out including say fins carrying some payload which is over here which is mounted using certain pylons these are the pylons here and this is the experimental vehicle.

So, this body is not entirely completely smooth then what happens. So, when the flow is occurring very high-speed flow is occurring you will have shocks from various such protrusions over the body and there will be an overall enveloping shock also. And these shock waves can interact with each other. So, for example in this case it is shown here that there is a shock from this generator.

So, a shock from this experimental vehicle over here can be formed here while the pylon itself can have a shock of this kind and these 2 shocks can interact with each other. So, when such Shock-Shock interaction occurs. Then many unexpected phenomena like sudden increase of heat transfer were observed and that caused severe damage. This is a certain damage that was caused in this case due to excessive heating and as a consequence part of the structure just melted away.

So, in the initial stages when for example while doing special design and. So, on people were yet trying to grasp about all the complexities involved in Hypersonic flow or in high-speed flow. Shock-Shock interaction phenomena came out to be an important problem. So, people have looked at it in detail and there are some interesting features there.

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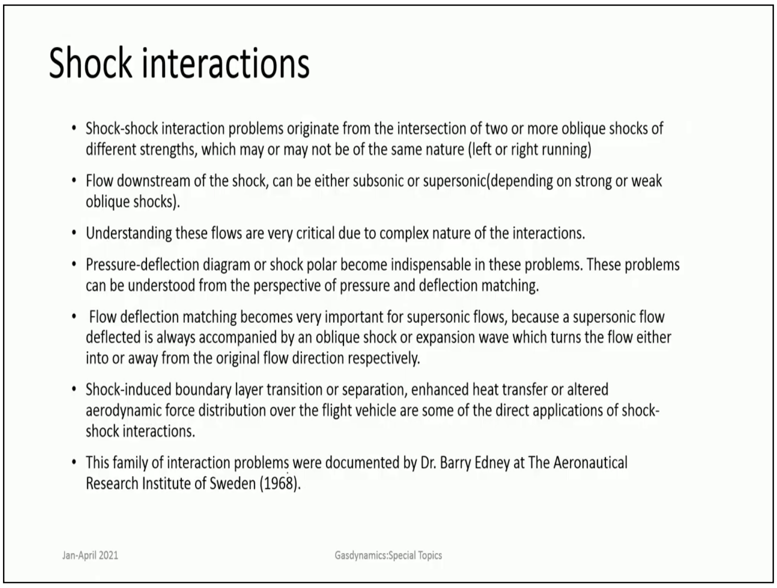

These continue to be studied because there is still lot more to be understood here. So, the Shock-Shock interactions can happen for any kind of different shocks they may be of the same and or a different kind, here kind means a family of shock which is left running or right running which we had discussed in the case of Oblique shock reflections, what we say as left running is if you have an upstream velocity coming this way and the shock is of this nature the flow turns towards itself.

So, towards the shock and this is having an angle theta right. So, now this kind of a shock turns the flow from the upstream direction it is turning the flow towards the right and this shock is known as a right running shock. While on the other hand if you had a shock of this in nature and this is the incoming flow it turns the flow towards the left.

So, this is known as left running shock. So, all other factors even if theta remains the same just the fact that it is turning the flow in different directions become important and when such shocks interact, they may be of the same kind both right running shocks or both left running shocks or opposite kind which means a right running and a left running shock interact. Then different kinds of flow features are produced.

Also, you can have a combination of subsonic and supersonic velocities downstream of such shock interactions. So, to study these shock interactions the pressure deflection diagrams are effectively used.

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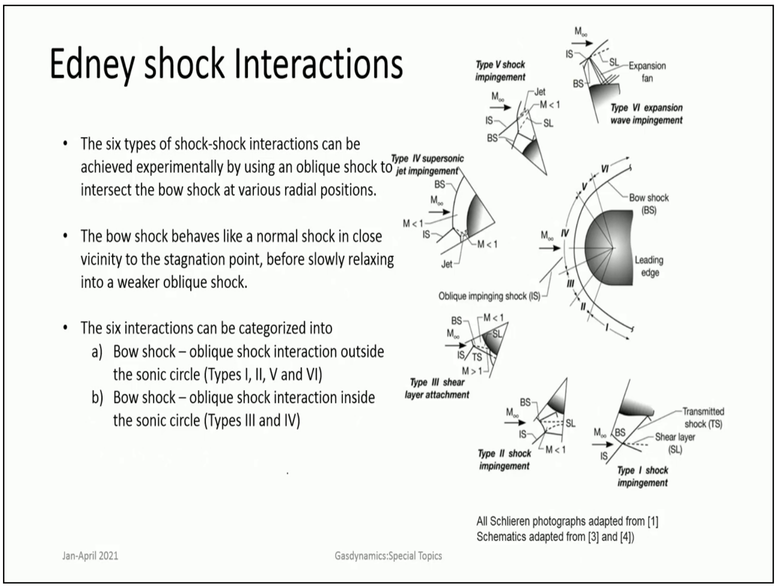

So, this becomes a very nice exercise to understand how to apply the pressure deflection diagrams in the case of multiple shocks. So, Edney carried out Barry Edney at aeronautical research institute of Sweden, he carried out set of studies and therefore after those studies he was able to classify the different shock interactions into 6 kind. He studied the interaction of a Bow shock ahead of a body, blunt body.

So, this Bow shock is an ideal candidate because it has various regions where the shocks have different strength. Far away from the nose the shock is essentially an Oblique shock while near the nose they are strong Oblique shocks and there is subsonic flow here. At a certain point there is a sonic line, and the flow becomes supersonic beyond the sonic line. So, within the sonic circle or sonic line the Mach numbers are less than 1 but beyond the sonic line Mach numbers are greater than 1.

So, you have both strong shocks and weak shocks in a Bow shock. Then what he did was use a shock generator a simple wedge and then create a shock and let it impinge on this Bow shock at different points and therefore produce different shock interactions. Later he found that there are 6 types of interactions 1 shock the interactions of shocks which are relatively weak which occurs in regions 1 and 2 and 5 and 6.

1 and 2 are interactions of Shock waves of opposite kind that is this is a right running shock, while the incoming shock is left running. While the 5 and 6 are interactions of shock with the same family, which is both are in this case both are left running. Now there are strong shocks in the regions 3 and 4 and interactions of shock in this strong shock region result in different kind of phenomena than the other ones.

So, there are 6 different types that are produced we will just go through the physical flow features of these interactions. Why this is important is in all these interactions what we find is that due to the Shock-Shock interaction there are shocks resulting shocks from the interaction which impinge on the body. Or in the case of the type 3 that is region 3 and region 4 interactions we have shear layers impinging on the body or there is a supersonic jet that impinges on the body.

When such discontinuities or supersonic jets impinge on the body, they can cause severe heating of the body at those locations. So, that is a consideration that has to be carefully considered while designing such bodies.

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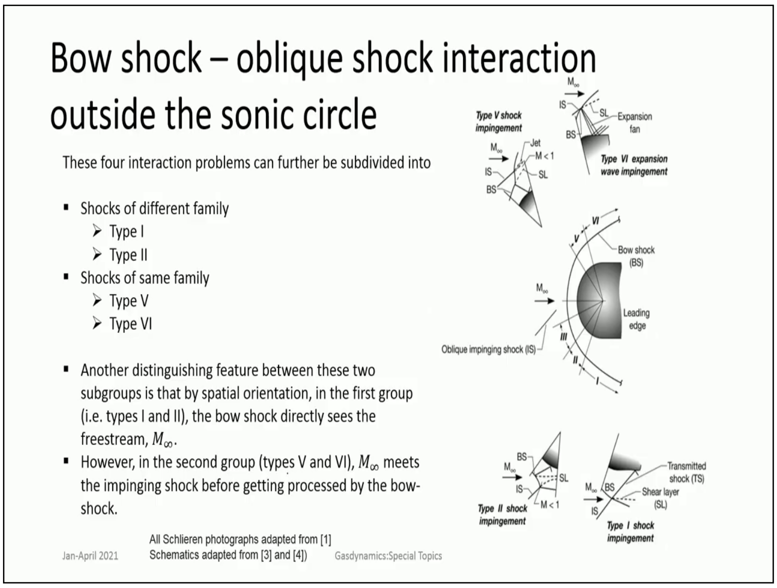

So, first let us just look at shock interactions happening with weak shocks away from the sonic circle beyond the sonic circle the flow is their shocks are relatively weak type 1 is a relatively weak shock. So, they are called as type 1, type 2, type 3, type 4, type 5, and type 6. In type 3 and 4 the shock interacts within the sonic circle where flow is subsonic after that.

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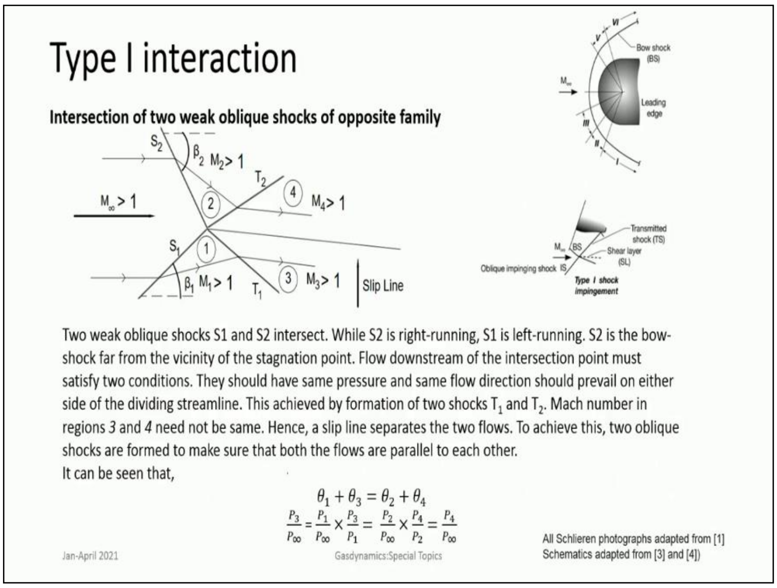

So, let us look at sharks first we look at type 1 interaction, here 2 shocks interact of opposite kind. So, this is a left running shock S_1, while S_2 is a right running shock, both shocks are relatively weak. So, consequently there are 2 other shocks that are formed T_1 and T_2 over here now the way to analyse them is to consider different Oblique shocks this is region in 0 or you can consider the free stream.

The flow passes through the first shock undergoes a deflection and it gets to region 1 thereafter it goes to region 3. Similarly in the upper half you get region 2 and then region 4. Then the boundary conditions at region 4, is that both these velocities at region 3 and region 4, V_3 is parallel to V_4. So, they have a parallel flow and there is no solid surface present here therefore $P_3 = P_4$, they are all Oblique shocks therefore the flow will be uniform in these regions.

So, only these conditions can be applied V_3 need not be equal to V_4. So, what we get here is a slip line across which velocities can be different, different temperatures can be different entropies will be different because they have different shock strengths, but the velocities will be parallel to each other and pressures will be the same. So, this is the boundary condition that can be applied, and we can.

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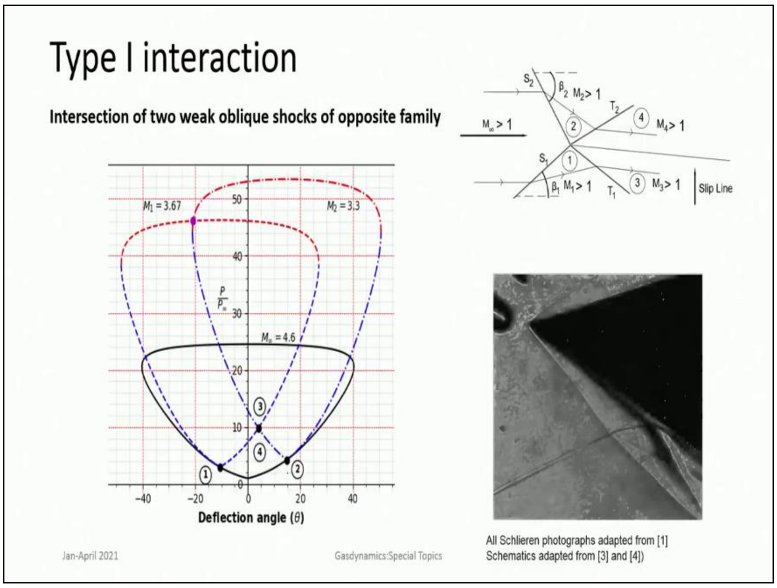

Then draw simple shock polar for this we can find out the base shock these are scaled shock polar plotted in actual coordinates. And this black line represents the upstream flow which is having Mach number of 4.6. The 2 shocks they are represented by this shock polar. So, you can see here this is one kind of a shock while the other one is in the opposite kind and they both intersect at this point which is 3, 4.

So, here there is a Schlieren of such weak interaction. So, you have one shock the other shock coming from here 2 other shocks are produced and the slip line is also visible faintly in this Schlieren. The main point here is this shock this transmitted shock over here can impinge on the body and there it can produce a spike of heat transfer pressure and.

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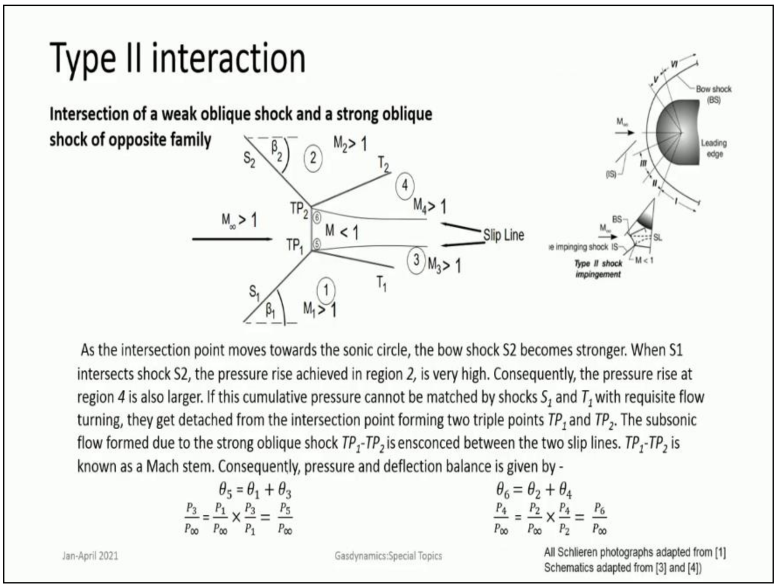

So, on now when we increase the strength of the shock further. So, from type 1 if we go towards type 2 which are stronger shocks. Then it may not be possible to have such just 2 shocks coming out because we know that all shock polar if you take there is a maximum flow deflection that can be done which is somewhere around this region, so, around this region. So, if the flow deflection produced by the flow due to the shocks when they interact when they interact if it is not possible to produce such a deflection.

Then we get a max stem instead here this is very much like Mach reflection that we discussed in case of reflection of shock waves and here you find that there are 2 triple points. So, this is the first shock here coming in there is a triple point for it there is a transmitted shock T_1 over here and a max stem here. Similarly corresponding to shock 2 you have another shock T_2 here and a max stem associated with it.

In between these 2 regions you have 2 slip lines. So, you have 2 slip lines in between which you have subsonic flow. These slip lines can respond and later they can form even sort of shape like a C-D nozzle and this Mach number which is less than 1 can get accelerated further to higher Mach numbers. But here this is a subsonic region which is separate from supersonic regions in 2, 4 similarly 1, 3.

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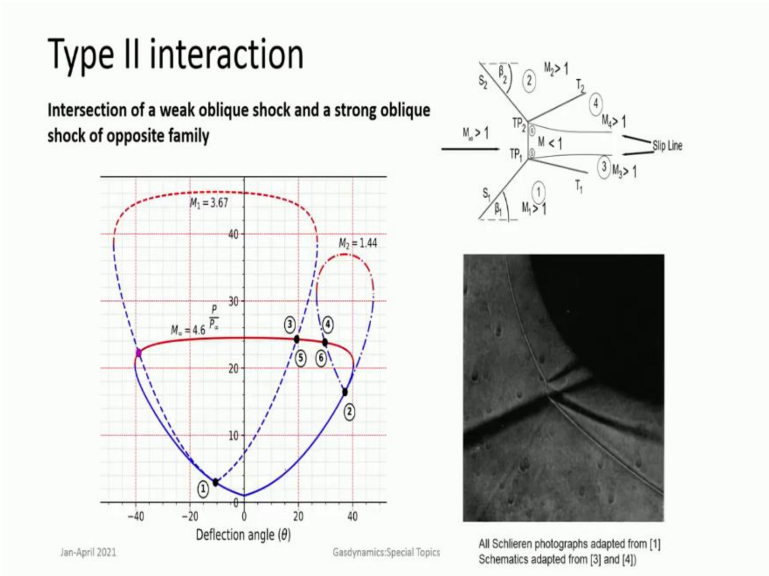

So, if we try to draw a shock polar for such interactions, we see it is possible to do that and here you find that this shock polar which is for Mach number 1.44 corresponding to a type 2 interaction does not have a solution where it intersects with any of the other shock polar but only at along the main shock polar. So, which is at this point, so, you have the 2 points here 3, 5 and 4, 6.

This is a Schlieren of such a shock interaction where you can see the shocks here and you can see there is a region very dark region which corresponds to the subsonic region. So, type 2 interactions happen when with a weak Oblique shock and a stronger Oblique shock they are of opposite families.

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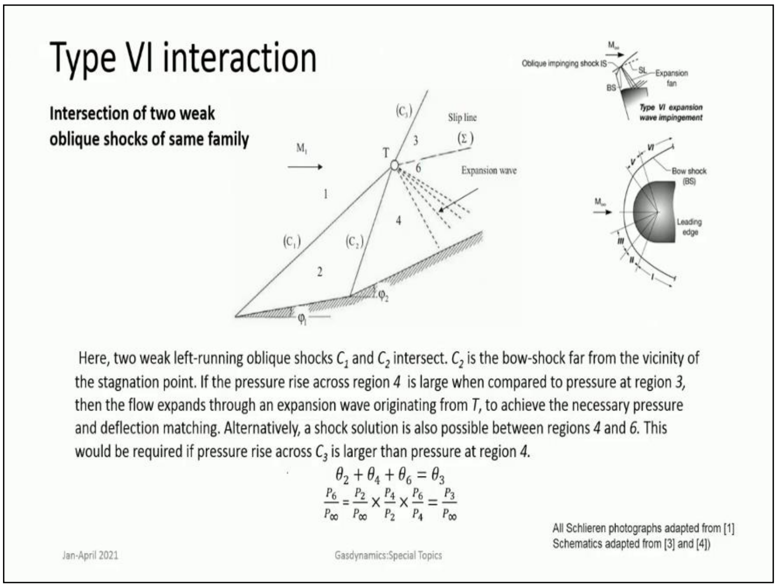

Now we come and look at again interactions of the weak kind not within the sonic circle. We look at type 6 interaction which occurs of with the same family. If you look at such interactions type 6 you see that there is already 1 shock. So, this is a 4-body shock C_1 this is the other shock C_2 they are of both same family and they interact at this point. Now what happens here is that you have the if you take a streamline over here it passes through 2 shocks while a strain line up here it passes through only 1 shock.

If the strengths are if you take the proper strengths, you find that pressure in 4 is larger than pressure in 3. So, pressure in 4 will be larger than pressure in 3. So, therefore an expansion fan develops and that makes pressures equal in 6 and 3. So, P_6 equal to P_3 and V_3 is parallel to V_6. So, this is what the boundary condition that we have there in type 6 interaction which can also be plotted in shock polar here.

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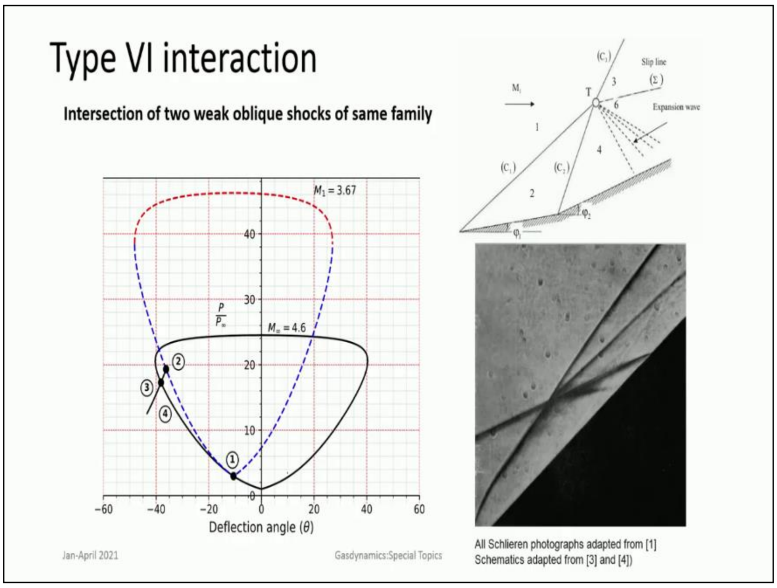

Here it represents a type 6 interaction where this is point 1 which is the point where the shock the point 1 is corresponding to here it is 0.2 this is slight difference in the kinds of nomenclatures that is followed. So, 0.2 corresponds to the region 0.1 corresponds to region 2 while the region that is 0.2 is here in point region 4 here and at that point an expansion fan develops therefore pressure decreases again and then we get the points 3 and 4 which is lying at this along the slip line.

So, and here is a Schlieren of the same in this case expansion fans what you see here they are expansion fans this dark region these expansion fans can impinge on the body.

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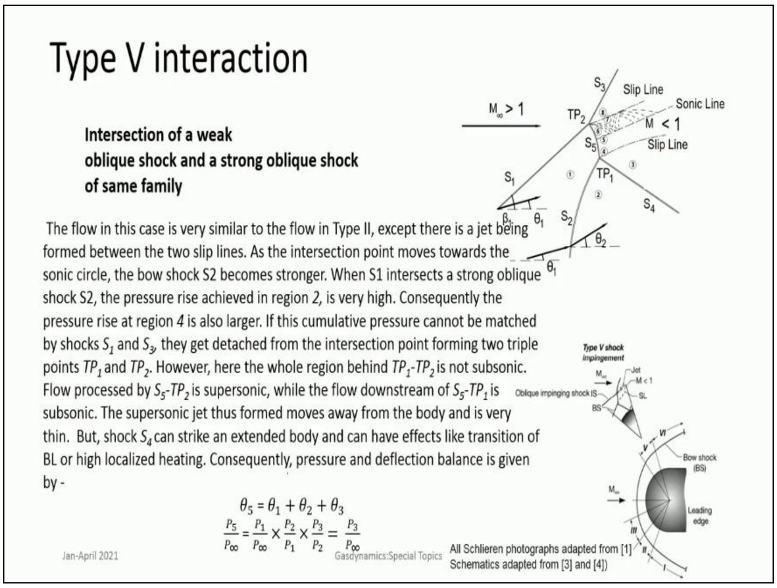

So, but these are relatively weak interactions type 6. Then we come to type 5 interaction in a type 5 interaction is. So, just like there was a distinction between type 1 and type 2 as the strength of shock increased. Similarly in type 5 here the strength of shock has increased compared to type 6 therefore again here you get a shock S_5 in between and this for creates a zone which is bounded by 2 slip lines and there is a supersonic flow.

So, now what happens is you will have expansion fans which are bouncing off 2 slip lines creating a kind of a jet here. So, you get a kind of jet in this place, but this jet is away from the body. So, it just curls away from the body does not come close to the body. The body is interacted with this by shock; this shock interacts with the body here.

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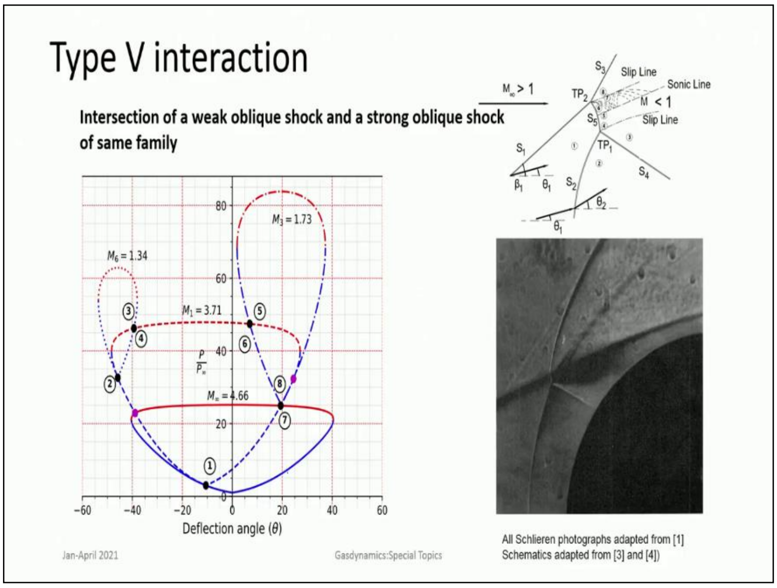

So, this is type 5 interactions which can also be seen in Schlieren's that are shown here in this region you have the 2 shocks. You have the region which containing the jet and the slip line is smudged in this case but essentially it is just the shock wave that interacts with this shock which interacts with the body. The corresponding shock polar can be drawn and we can understand shock interactions very well with shock polar.

So, this is 1 application where shock pullers can be used to a good extent it is very difficult to solve all these algebraic equations where we get a system which is quite large and having many constraints. So, if we plot it graphically it is easier to understand them. So, in type 5 interaction we get a couple of slip lines and a sort of a jet that occurs between them.

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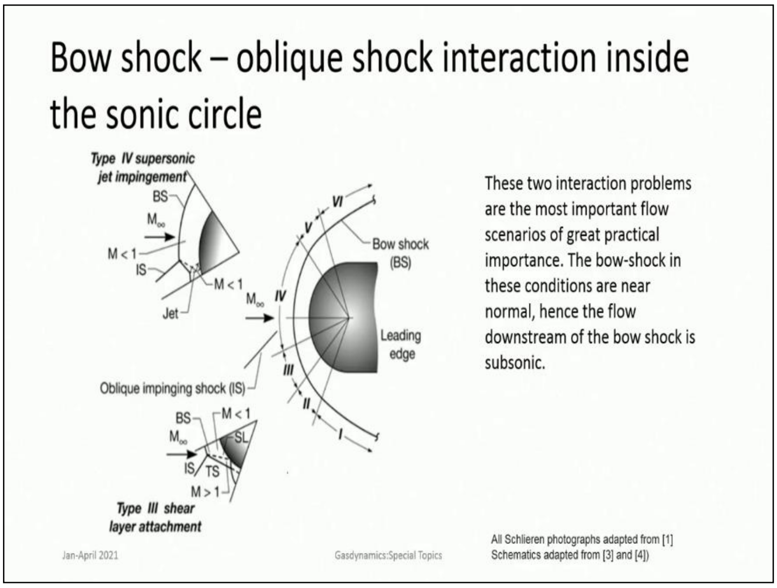

Now if we move to the interaction Shock-Shock interaction with which is very close to the sonic circle within the sonic circle? What happens here in this region 3 and region 4 they are called type 3 and type 4. Here the Bow shock is of very high strength, strength is larger flow downstream of the Bow shock is subsonic. So, that is quite different from the cases in type 1 type 2 or type 5, type 6 which had supersonic flows downstream.

So, they produce certain special features which create lot of changes on the body and as a result they are of immense importance when looking at bodies.

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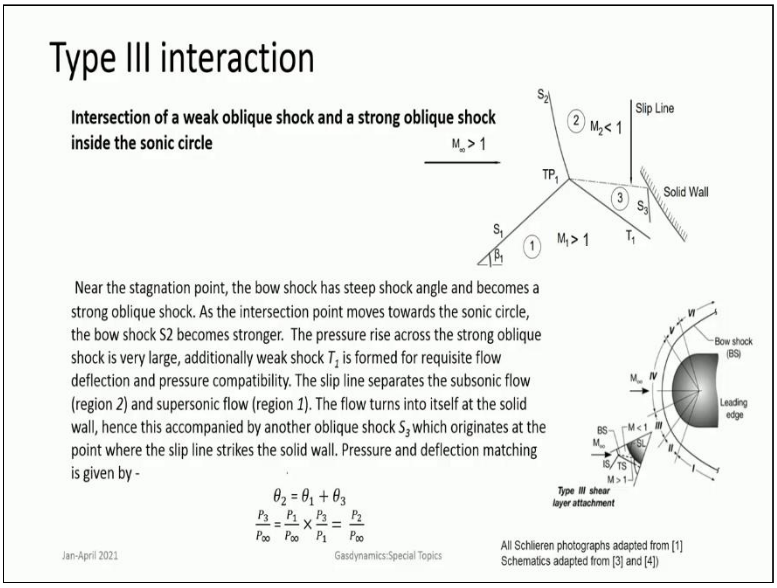

Let us consider the type 3 interaction in type 3 interaction this is the impinging shock S_1 this is the Bow shock S_2 and here a slip line is formed between 2 regions which is first region 2 which is downstream of a strong shock. So, subsonic flow here $M_2 < 1$, but region 3 which is downstream of an Oblique shock. So, in region 3 Mach number is greater than 1 a slip line is formed which intersects the solid wall.

Now this supersonic flow here which is Mach number is greater than 1 must be turned to an angle at the solid wall consequently another shock S_3, S_3 develops over here. So, this is the flow feature you have a slip line or a shear layer impinging on the solid wall therefore you can get an increase of heat transfer at that location followed by a production of a shock wave also.

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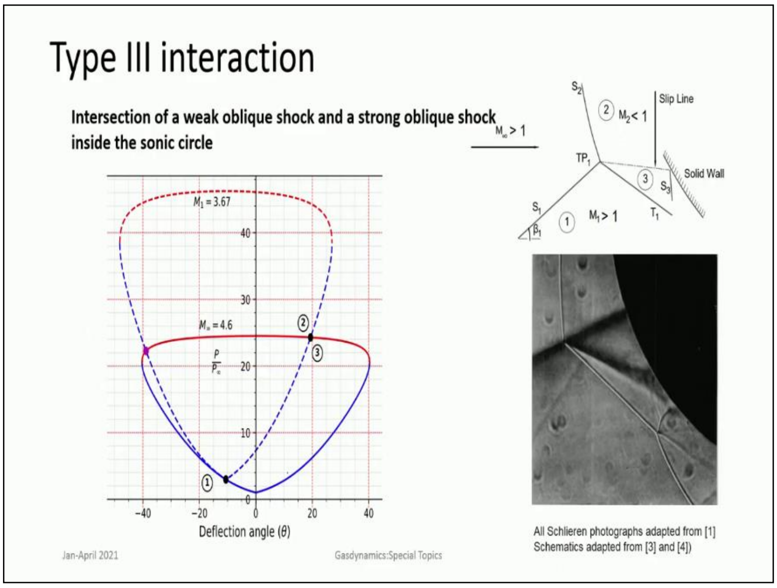

So, this is the flow picture for Schlieren of such an image. So, here you can see these are the shocks and here you have the slip line originating over here and impinging on the body around this region. The corresponding shock polar it is drawn for the triple point TP_1 and 0.213 are located here.

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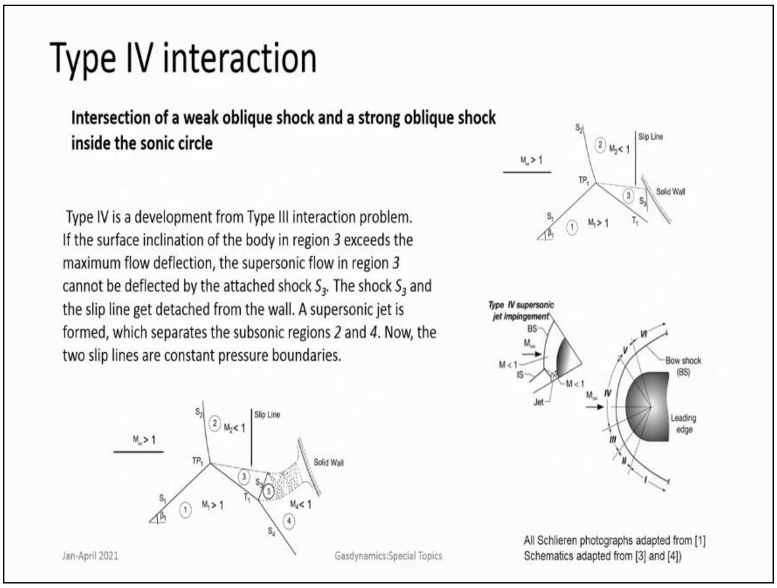

Now we can go to the most special case which is the type 4 interaction. In type 4 interaction the interaction happens very close to the stagnation region. So, much stronger shocks and if we compare it with type 3 in type 3 there is a shear layer or slip line which comes and interacts with the wall and to turn the flow that is turn the flow parallel to the wall a shock S_3 develops.

If the angle of the solid wall is increased further. Then there may not be an attached solution for S_3 which is attached to the wall. In such scenario the type 4 interaction forms. In type 4 interaction there is the formation of S_3 over here you get 2 regions which in which case this is region 2 where it is subsonic flow similarly region 4 which is subsonic flow. So, here it is subsonic flow here also it is subsonic flow.

But in between this there is a region 3 which is having a supersonic flow and it is bounded by slip lines and. Then you can have shock waves and expansion fans reflecting off these 2 slip lines which are constant pressure boundaries. This is very much like a supersonic jet and this can impinge on the solid wall create very significant increase in pressure as well as heat transfer.

That is the reason why this type of interaction is very important from the perspective of controlling the heat transfer on bodies.

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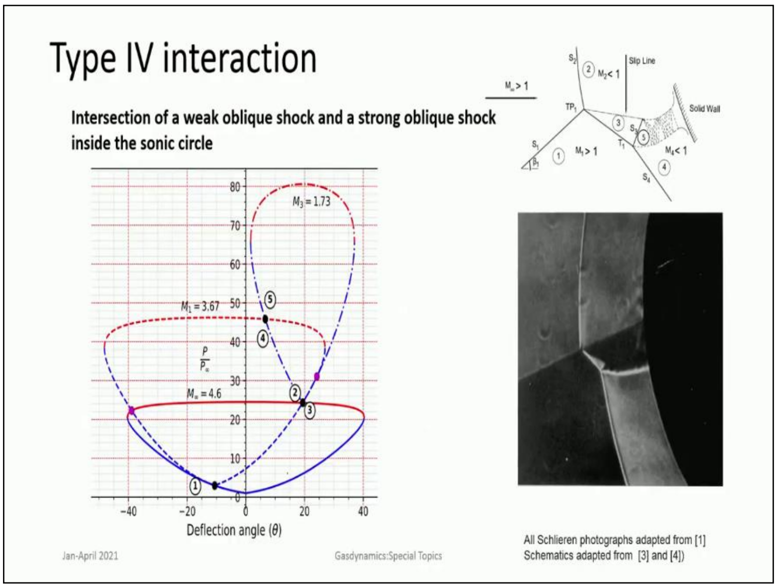

So, we have seen that there are 6 types of interactions very interesting different kinds of flow features produced when the Oblique shocks interact with each other. They are important in the context of looking at designing bodies because normally we consider that stagnation point is where the highest temperatures are produced and therefore high heat flux is produced.

But if shock interactions take place there may be other regions where these interactions can produce significant heating and that must be considered carefully. So, this was a and again another brief introduction into such interesting flow features as shock-shock interactions. They can be studied using Schlieren methods as well as drawing shock polar and understanding them and their flow features.

So, they are also found in many other flow scenarios which we will see soon that if we consider the viscous effects at the wall. Then we always must consider a layer which is close to the wall where viscous effects are important which is boundary layer and when we come to supersonic flows there are always shocks that are present and when shock interacts with the boundary layer.

Then what happens again set of interesting flow features are produced we can look at that in the coming classes. So, thank you.