Aerodynamic Design of Axial Flow Compressors & Fans

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Lecture 51

Transonic Compressors (Contd.)

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Hello, and welcome to lecture 51. We are discussing about the Transonic Compressors.

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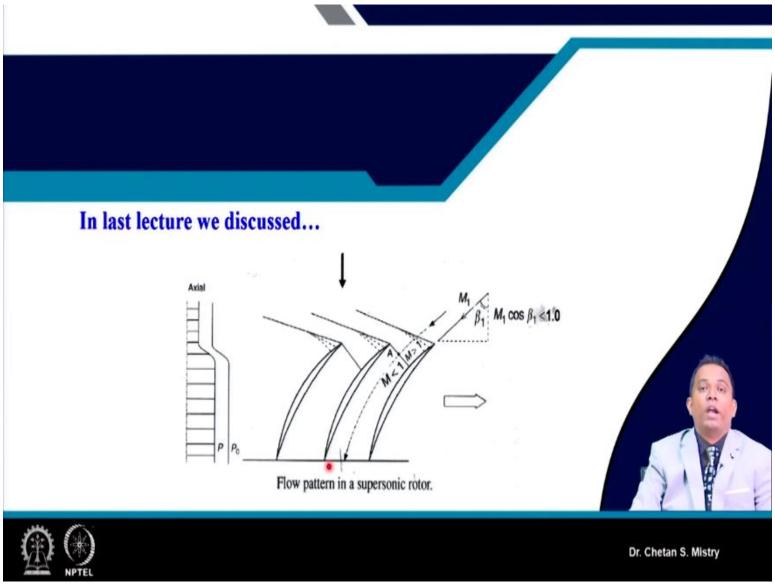

In last lecture, we were discussing about how the flow, that’s what will behaving, when we are talking about supersonic flow. So, here in this case, if we consider, we have discussed, we are talking about the relative velocity component, that’s what is going to be supersonic. So, this

M_1, that’s what is say relative velocity component, that’s what is say supersonic, this is what is my axial velocity component, which may be say subsonic in configuration; at this moment, this is what is subsonic in the case.

Now, when this flow that will be incident on say airfoil, this airfoil, that’s what is of sharp edge nature. So, here because of its sharp nature, the shock will get anchored. So, this will get anchored here at the leading edge.

Now, when it will be anchored at the leading edge, one leg of this shock that will be moving away from the blade, and second leg, that will be moving inside my flow passage. So, here this is what is moving away from the blade and this is what is moving inside my blade passage. Now, because of this curvature of my suction surface, and the inclination here with the oblique shock, that’s what will be generating here, the curvature or say, that’s what is we are defining as say expansion fans. So, this curve, that’s what is moving away from the surface and that is the reason why we are having expansion fans which has been formed.

Now, when it will be moving downside, here somewhere, as we have discussed say oblique shock that will be striking on the suction surface of the next coming blade. Now, this is sometimes people they are defining as a passage shock, okay, and this shock is of normal nature, or we can say it is approximately or near to normal shock. And that is the reason why we are having sudden jump of say Mach number from supersonic to subsonic. And that’s what is giving me sudden rise of pressure.

Now, downside, if you look at, this is what is my subsonic flow in the downward direction. And that is the reason why here in this whole flow passage, I will be having subsonic diffusion. Now, in order to understand this is what is representing how my pressure and total pressure that’s what is varying in axial direction.

So, we can say here, say…once it will be reaching at this shock, we will be having sudden rise of static pressure as well as total pressure and to our requirement, we can understand, we are getting sudden rise in pressure, we can understand we are talking about the pressure rise expected more than 1.4, maybe 1.6-1.8 or maybe 2. So, such kind of diffusion or such kind of pressure rise, that’s what we can achieve by having this kind of shock mechanism.

So up till now, when we were discussing about the axial flow compressor, we used to say this shock, that’s what is creating trouble. And that is the reason we are looking for avoiding the flow to go to say supersonic. Now, once people, researchers, they realize this is what can be taken as a benefit, and that's what has attracted attention towards the development of new airfoils.

And, this airfoil we can say, this is what is called supersonic airfoil. Here, the edge, that's what is sharp edge at the leading edge, the say…end, that's what is called say trailing edge, that is also of sharp nature. So, you know, once we realize the benefit of taking say shock mechanism, say new innovative idea, that's what has come into existence.

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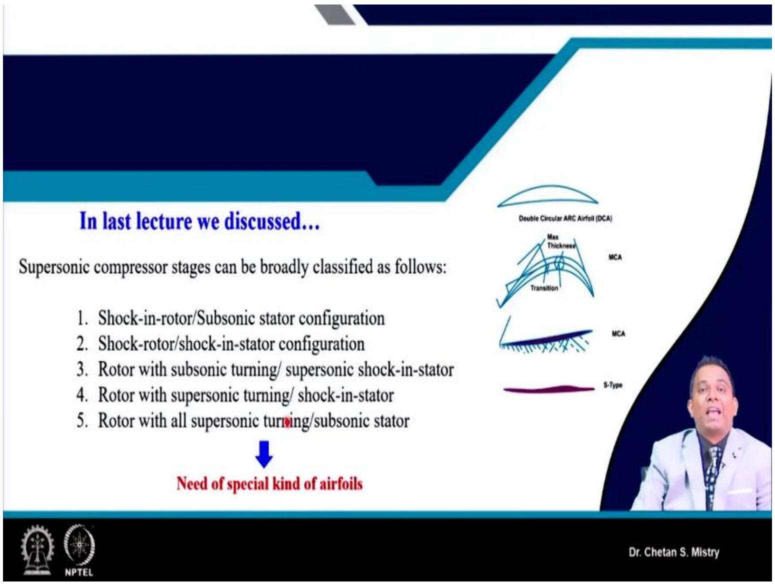

And, we have discussed, there are different kinds of configuration people over the year, they have explored. Say, during 50s, 60s, 70s and 80s, people, they started exploring different possibilities for say supersonic compressor specially. Say one, it says shock in rotor - subsonic stator configuration.

So, the shock formation, that's what will be happening inside your rotor passage and whole the stator that will be subsonic. In some other configuration, shock rotor and shock in stator configuration, that is also possible. So, a whole lot of diffusion, that's what has been done in say stator. Specially, whole acceleration of the flow, that's what will be going inside the rotor and at the exit, we will be having our absolute velocity, that's what is going to be supersonic.

And that supersonic flow when it will be striking on my stator, the stator will be acting like a supersonic stator or that's what will be giving the supersonic flow formation within. And, we can say that as say shock in stator. Some other configuration it says rotor with subsonic turning and supersonic shock in stator, rotor with supersonic turning, shock in stator, rotor with supersonic turning and subsonic stator. So, all kinds of possibilities people they have explored and that’s what has given new say vision in order to develop say per stage pressure rise to be very high and that’s what has given a whole new thought process for the design and development of axial flow compressor.

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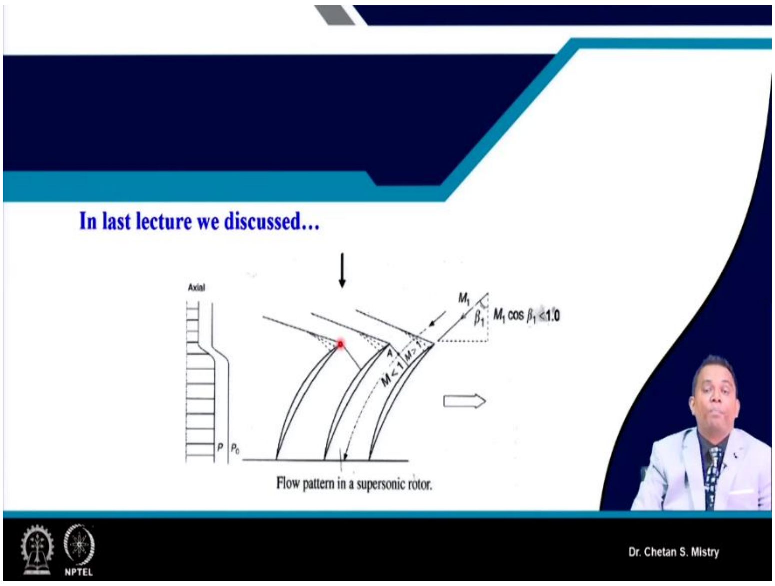

Now, here in this case, if we look at carefully, say we have seen these airfoils what we are talking of, these airfoils are different compared to what we have studied for say our subsonic compressor. What is the structure difference?

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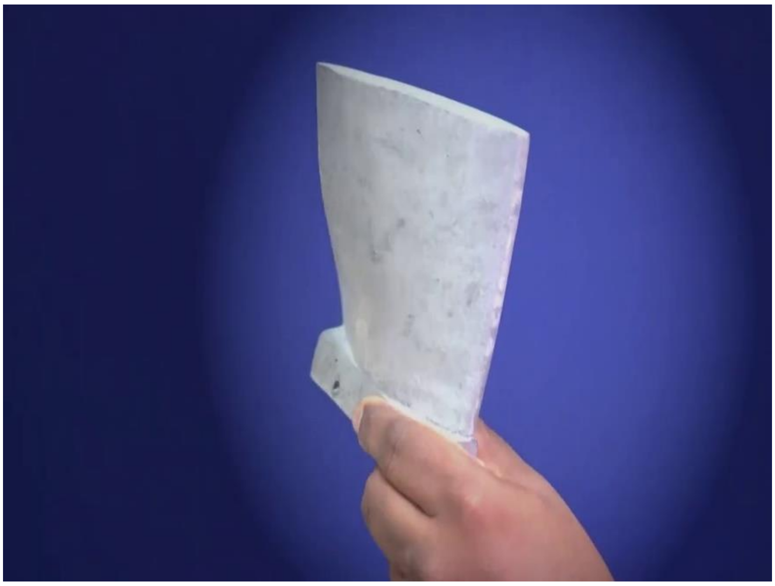

So, here in this case, so, this is what is representing subsonic compressor blade; here in this case, if we look at, this is what is our leading edge, we can say this is what is our trailing edge and this is what is the airfoil.

This particular, that’s what is representing my suction surface, this is what is representing my pressure surface. And if we look at carefully, this leading edge, that’s what is say maybe of circular shape or maybe of say elliptical shape. What will happen when my flow that will incident here we will be having the acceleration of flow, that’s what is happening on my suction surface and then after later part it is subjected to say deceleration. Inline to that, say for pressure surface also, we will be having the flow acceleration that will be happening up to some extent and then after later part, we will be having say constant Mach number or constant pressure rise kind of configuration.

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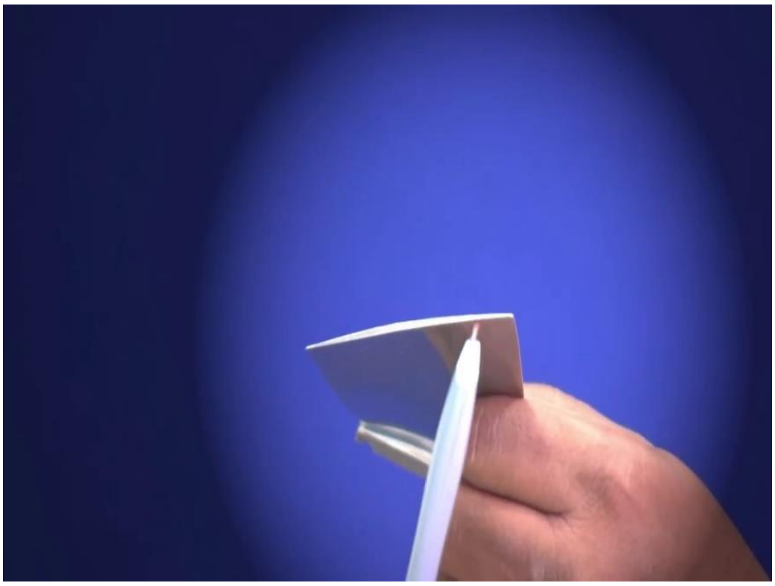

When we say we are having say…supersonic blade; so, this is what is representing supersonic blade. Here, this is what is representing the leading edge of the blade and here this is what is representing my trailing edge. And, if we look at carefully, this is what is having some different kind of shape, okay. Now, if we look at for the blade, this is what is representing my suction surface and downside that's what is representing the pressure surface. As we have discussed, here we are having our leading edge, that's what is not exactly the sharp one, but it is slightly rounded.

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Same way, this trailing edge also is of slight rounded. If we try to compare these two blades, what will happen? As we have discussed, because of formation of shock, we will be having acceleration, that's what is happening up to certain extent on my suction surface.

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While in the case of subsonic blade, when we say subsonic blade, say for subsonic blade what happens, I will be having my acceleration, that’s what is happening because of my curvature, okay.

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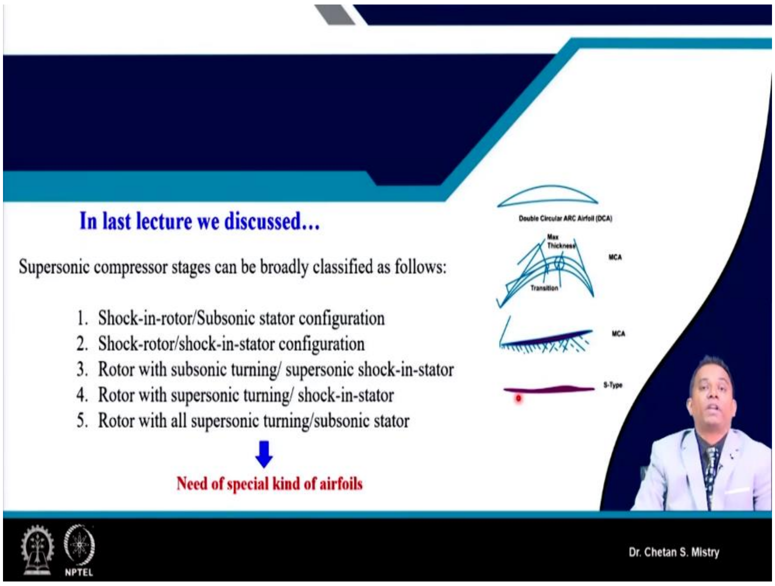

So, this is what is making the whole difference here. Now, here in order to understand this part, what we are looking for is say, we are looking for some special kinds of airfoils. Because if we consider when we are having say rounded shape, if you are having a rounded leading edge, that’s what will be acting like a blunt surface and when my shock that will be striking on that, that will not give say attached shock or maybe it will be giving the bow shock.

So, under this condition, this rounded leading edge with thickness, that's what will not be applicable, okay. Same way, if we are looking for say our leading edge for say…transonic airfoils, those transonic airfoils if you are making that to be sharper one, then it will be acting well, when it is working under one flow condition.

We know our compressor, that's what is working under off design condition mostly. Suppose if we are talking about the commercial aircraft, or we are talking about say military aircraft, for both the configuration most of the time my compressor, that's what will be working under say off design condition.

Under off design condition, when this flow that will be striking on the sharp edge, it may be possible that what flow pattern or what shock pattern we are expecting that may not happen; under subsonic condition, it may possible that my whole airfoil or my whole blade that will go under stall condition. And, literally it will go under the surge condition and we know when it is going under surge condition, that's what is making catastrophic failure of our engine.

So, we need to be very careful in sense of having airfoils. Now, the situation is we want to take the benefit of say supersonic flow and in order to have the supersonic flow with minimum losses, we need to manage the flow within the flow passage or within the blades. And that is the reason why we are discussing or we have already discussed about say Double Circular Arc airfoil, we can say we are having one circular arc, this is what is say our second circular arc.

And, that's what is not having exactly sharp edge, that's what is rounded with small radius both at leading edge and trailing edge. Now, this is what is representing the Multiple Circular Arc where we are having say four different circular arcs; we can say this is what is one circular arc, second circular arc, third circular arc and fourth circular arc.

The flexibility here is as per the requirement, we can change the radius or the curve of suction surface, front portion, suction surface, rear surface, maybe towards the leading edge, we can modify our flow passage, towards trailing edge also we can modify our passage and most flexibility that's what is because of presence of maximum…say…maximum thickness.

For Double Circular Arc, this maximum thickness, that's what is placed at say 50% chord, and for Multiple Circular Arc, we are having flexibility to move this forward or backward means towards leading edge or towards the trailing edge. And, that's what will be helping us in managing the flow.

Now, this is what is of one kind of Multiple Circular Arc, that's what is having say straight nature towards the leading edge and later on that's what will having say circular shape…say…camber line what we have. Similarly, this is what is called shallow type airfoil or we can say S type airfoil. So, today we will be discussing in detail, what is this DCA airfoil, MCA airfoil, S type airfoil and how the flow, that's what we will be having. And, that's what we will be giving us idea how we need to think as a designer as an aerodynamicist. So that, we will be getting what we are expecting for future development of aero engines with per stage pressure rise to be very high.

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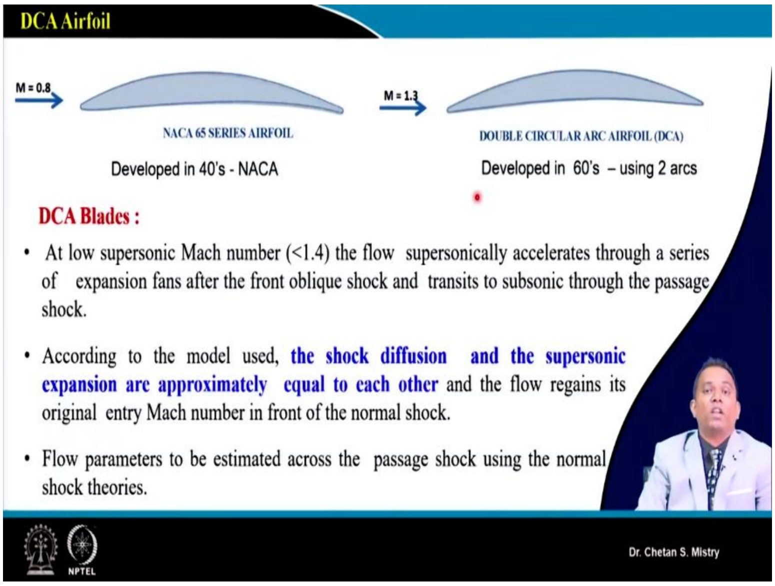

Now, here, in this case, if we look at, this is what we have seen, we already have discussed, that's what is say, NACA 65 airfoil. So, this NACA 65 airfoil, that's what was developed by say NASA during say 40s. And later on, that's what was used for say slightly high subsonic flow, maybe in the range of 0.8. What happens here, when my flow, that's what is moving on the suction surface, somewhere here, maybe 40% or 50% of our chord, we will be having our flow to be supersonic, because this is what is subjected to the acceleration of the flow.

And later on, that's what will be giving the deceleration of the flow when it is moving downwards towards the trailing edge. Now, because of flow behavior, that's what is acting in little critical way, that's what will be subjected to give very high losses. And, that's what was putting constraint for using this say NACA 65 series, specially for the transonic or supersonic compressors.

Now, the thing is, in order to overcome this kind of difficulty, people they move with say Double Circular Arc. As we have discussed, this is what was the airfoil It was developed during 60s. So, here we are having say one circular arc, this is what is my second circular arc, and we can say our leading edge and trailing they are slightly rounded one. We are looking for our flow not to be very sensitive with these sharp edges. Here, in this case, my flow that's what will we be having nicely on suction surface as per the expectation and later part also it will be giving say diffusion.

So, specially for double circular are, we can say we are having two type of diffusion, that's what is happening. One, that's what is say supersonic diffusion; second, that's what we can say as a subsonic diffusion. So, it says, mostly for low supersonic Mach number, of the order of 1.4, my flow, that's what we will be supersonically accelerated through the series of expansion fans, then we will be having say normal shock, and then the flow will be subjected to subsonic flow.

According to the method what we use, the shock diffusion and supersonic expansion are approximately same. Now, in order to understand the flow behavior, we are using our fundamentals what we have already studied, or what we know from our basics of gas dynamics. It is preferred just brush up the knowledge of shock formation, we can say oblique shock, normal shock, then just learn how to look at the flow table. That's what will be helping us in sense of understanding the variation of different flow parameters.

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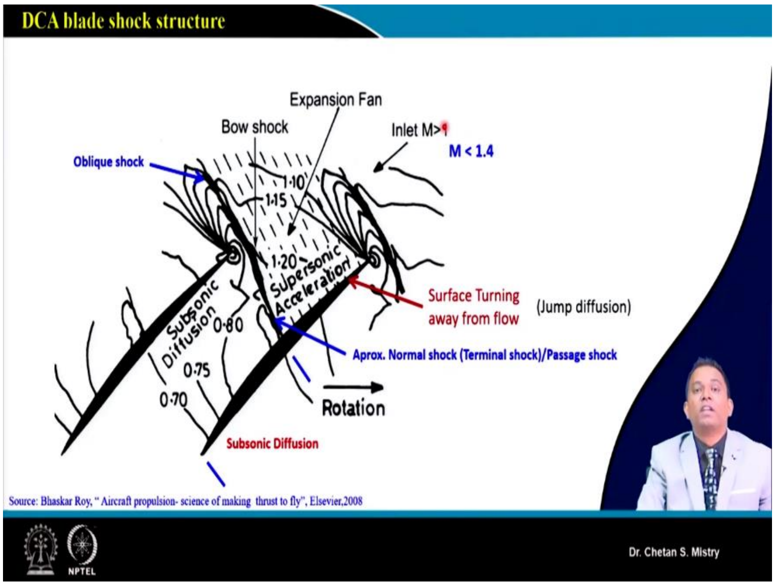

Now, in order to realize what exactly is happening, this is what is computational study, which was been reported in open literature. Now, here in this case, if you look at, this is what is our leading edge, this leading edge is blunt leading edge, we can say it is a slightly rounded leading edge. And, because of presence of this leading edge, we are having the bow shock that's what will be standing in front of our airfoil. Now, what happens, this bow shock, we know, that's what will be having say formation like oblique shock; one leg of this oblique shock that will be moving away from the blade, and second leg, as we have discussed, that's what we will be moving in the flow passage. So, this is what is my second leg, that's what is moving within my blade passage.

Now, what happens? Here in this case from our fundamentals of gas dynamics, and what we learn for say shock formation and expansion fan formation, when we are having our surface turning away from the flow, so here if you look at, my surface, that's what is turning away from the flow and that is the reason why we are having the formation of expansion fans. So, we can say here, we are having expansion fans, that's what will be forming.

And, once it will be reaching or moving towards this location, what we say as a passage shock or we can say that as say normal shock location, we will be having the change of property. Change of property in the sense we will be having flow that will be converted or it will be downside subsonic. So here, we will be having our flow to be say supersonic and downside of that we will be having our flow to be subsonic. So, this is what will be bringing say sudden jump of pressure. Sometimes, people used to define this kind of diffusion as say jump diffusion, okay.

Now, for later part, if we look at carefully, this is what has been shaped like our diffuser, that's what we used to learn till now. So, you know, this passage area, that's what is say lower passage area; my exit passage area, that's what will be larger, and that's what will be giving subsonic diffusion.

So here in this case, with Double Circular Arc, we are able to manage say supersonic diffusion as well as our say subsonic diffusion. But the thing is, here this kind of airfoil, that's what is having limited application up to Mach number of 1.4. Now, as we have discussed, we are looking for very high pressure rise, when we are looking for per stage pressure rise to be very high, under that condition maybe we need to go with the high rotational speed or maybe if we are talking about the fan, it will be having larger diameter.

Under that condition, it may be possible that we will be having our inlet Mach number that will be in the range of 1.6-1.8 or maybe 2. So, under that circumstances, these blades, that's what is having certain limitations, okay. So, we will be discussing how to get rid of this kind of difficulties. Say, this is what all we are discussing in sense of flow behavior, that's what is happening for DCA blade.

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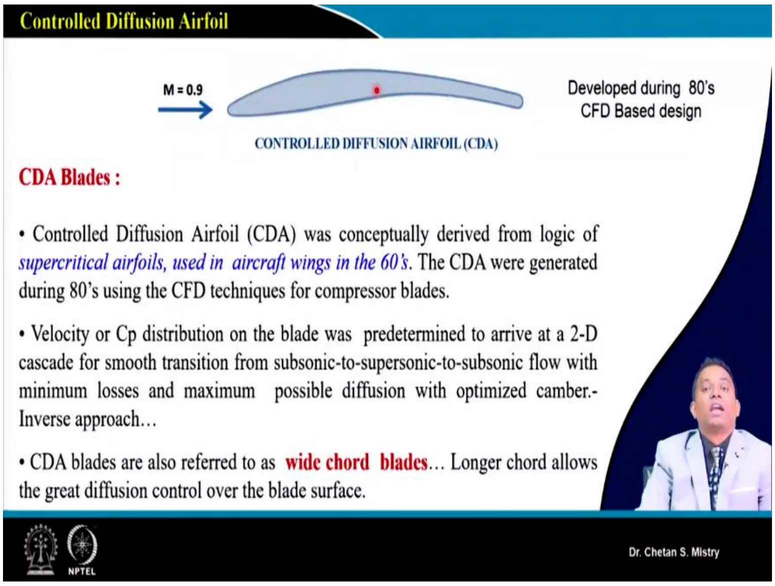

Now, one more development, that's what was done during 80's. So, that time the computational tools, what we say CFD, that's what was getting matured. So, by using those computational fluid dynamics tools, this airfoil, that's what has been developed. So, here if you look at, this is what is having a different shape compared to what all we have seen in sense of Double Circular Arc. Here if you look at, this is what is having say boomerang shape.

Now, these airfoils, that's what has been developed based on the fundamental understanding of supercritical airfoils. Those supercritical airfoils which were been used for say development of aeroplane wings during 60s. Now, using CFD technique, this airfoil it has been developed. Here, let me put the point, say this airfoil when it was being generated, it was been decided with particular pressure distribution both on pressure surface and suction surface; we can say as say C_p distribution, okay.

And, we will be having say control of velocity on this airfoil. So, we can say, those days, people, they have developed this airfoil with the concept of inverse design, where predefined pressure distribution, that's what has been known to us; and, from there, airfoil shape that need to be developed, okay. And, that's what has given very good idea or new innovative idea for future development. Now, what all airfoils, what all blades for fans, compressors, we are looking at, those all airfoils, they are been developed using the computational tools, okay.

Now, here you can say, initially as we were discussing, earlier also, initially you assumed some airfoil shape, and later on, as per your expectation maybe you modify your shape. Suppose, if we consider this is what is say CDA airfoil, maybe at the initial stage you consider say Double Circular Arc airfoil and later on as per the expectation of your flow on the blade surface, the shape will get modified and this is what is say new kind of airfoil.

And, as I used to say, this is what is coming as a proprietary nature of work. So, all engine manufacturing companies, they are having whole lot of database, that's what is already been available with them. And even as on today also, they are developing new kind of airfoils to meet their specific requirement. And those all are of proprietary nature. So, this is what is innovative way of development of blades.

If we look at carefully, this blade seems to be wide chord, we can say the length, or we can chord of this blade, that's what is say large. And, that's what will be giving effective diffusion that's what will be happening on my blade surface. So, recent trend, if we recall, we were discussing about some low aspect ratio fans, where people, they were using wide chord blades, those wide chord blades, they are having this kind of airfoil to be used, that's what they say Controlled Diffusion Airfoil (CDA).

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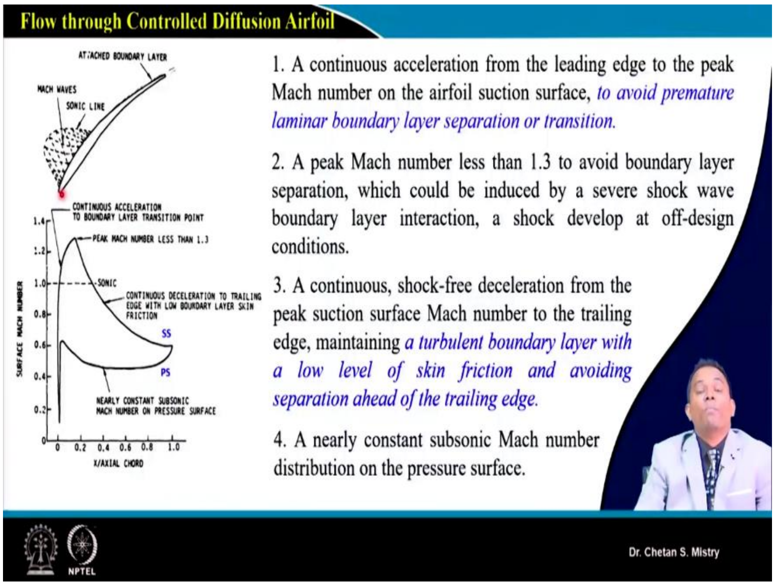

Now, let us try to understand what exactly is happening on the flow surface or on the blade surface. So here, this is what is representing say CDA airfoil. Now, on the suction surface, if we look at, we will be having the formation of shock on the surface. We can say, we will be having whole lot of acceleration, that's what will be happening on the suction surface, it will be reaching the Mach number in the range of 1.3, you can see here, this is what is say nearly 1.3.

Now, what is the benefit of that…say…they used to say, this is what we will be avoiding say premature laminar boundary layer separation or transition, that's what is lead to flow separation in the later stage, that's what is giving say formation of profile losses at the end, near the trailing edge; and, that's what will be increasing the losses. Now, in order to avoid that kind of phenomena, this is what has been specially been designed.

Now, here in the later part, if you are looking at, say continuous shock free deceleration, that's what will be happening from this peak Mach number towards the trailing edge. The turbulent boundary layer with low level of say skin friction and that's what will be avoiding the flow separation to be happenned on the trailing edge.

Now, if we look at what is happening on the pressure surface; there also, for initial stage we will be having acceleration and later part we can say we are having nearly constant subsonic flow on the pressure surface. So, this is what is say Controlled Diffusion kind of airfoil. So, now people, they are having this kind of understanding, say detail flow field study and based on say computational tool, we are able to manage; basically, if we try to look at what we are doing is we are managing our flow between two airfoils, okay.

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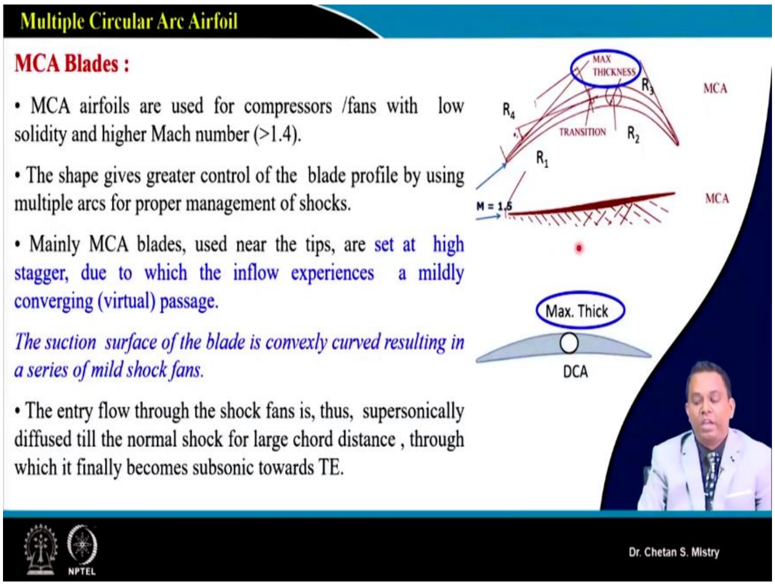

Now, after this, say when we are having say Mach number in the range of 1.4, we can say, we will move with say DCA or maybe we can go with say CDA. We are always crazy, we are looking for higher and higher numbers! Suppose, if we consider say we are looking for Mach number in the range of 1.6, it may be possible that DCA will not work as per our expectation because my flow management within the blade passage is very important there. Here in this case, this is what is being used for highly staggered blade. So, if we look the fans, say high bypass ratio fans, near the tip region mostly where we will be having those blades to be highly staggered, okay. So, we are having our flow, that's what we need to manage in a systematic way.

So, here if you look at, this is what is representing say Multiple Circular Arc airfoil. And, speciality we can see compared to our Double Circular Arc, here we are having say straight line cambered up to certain distance and then after that's what is having some curvature, okay. If we compare with say Double Circular Arc, here in this case, we are having say curvature for the suction surface. And at the same time, as we have discussed earlier, our maximum thickness location, that's what is somewhat different.

So, here for Double Circular Arc, my maximum thickness, that's what will be placed at say mid chord; here in this case, we can adjust. Let us see how my flow that's what will be behaving for Multiple Circular Arc kind of airfoils.

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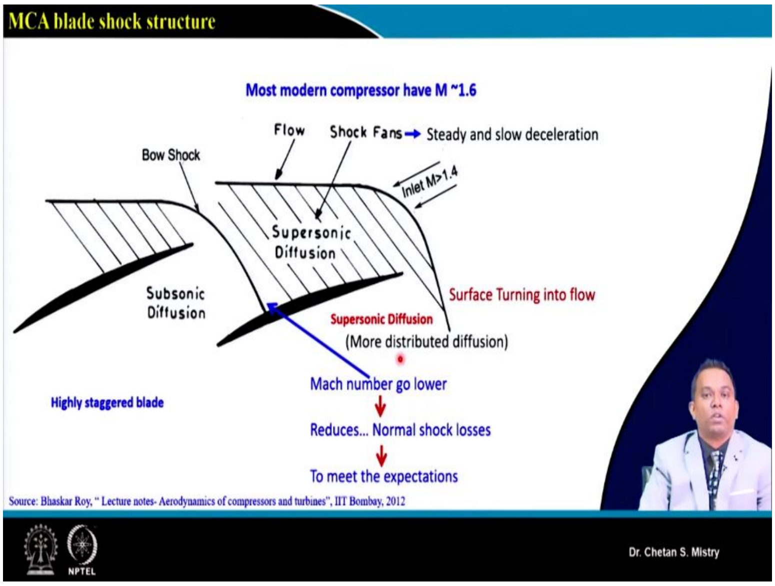

So, this is what is representing say Multiple Circular Arc. So, these blades are say highly staggered blades and if you look at carefully we are having one circular arc, second circular arc, third circular arc and fourth circular arc; do not get confused this is not your Double Circular Arc, okay. Now, what happens? Because this is what is say highly staggered, my flow when it will be incident on say blade, it will be subjected to have this kind of bow shock to be formed.

In line to what all we have discussed, we will be having formation of shock; one leg, that's what will be moving away from our blade; and second shock or second leg, that will be striking on say next coming blade.

Here if we try to look at carefully, and if we are comparing our Double Circular Arc, we can see, this striking of shock or say presence of passage shock, that's what is more towards the trailing edge. In the case of Double Circular Arc, this passage shock it was around say 40% of my chord from the leading edge.

Here in this case, this is what is striking more towards the trailing edge. Basically what happens? Say, this curvature for the suction surface it is been made in such a way that my surface, that's what is turning into the flow and that is the reason why here we will be having formation of say shock fans. So, this is what is say shock fans.

They are steady and if we look at carefully, what happens because of formation of the shock fans, my flow initially will be say supersonic; slowly, it will get decelerated at the time when it will be reaching towards the passage shock, it will be having low subsonic, or say low supersonic Mach number, in this particular region.

And, from there it will be subjected to normal shock and downside we will be having say subsonic flow. So, we can realize here, we are having say whole lot of diffusion, that's what is happening because of our supersonic flow or supersonic diffusion; only small extent towards the trailing edge, which is responsible for say subsonic diffusion. And, that's what we are looking for, okay.

Now, the benefit of having this kind of normal shock on the trailing edge side, that's what will be giving the reduction in the losses, because of flow separation. We can say here, there is a sudden jump of pressure, that's what is happening and because of adverse pressure gradient, it may be possible that my flow will get separated from that region. But because we are having that more away from say my leading edge or towards the trailing edge, and that is the reason why this losses are going low.

We can say, this is what is not jump diffusion, this is what has been defined as say more distributed distribution, or a more distributed say diffusion, that's what is happening on my blade.

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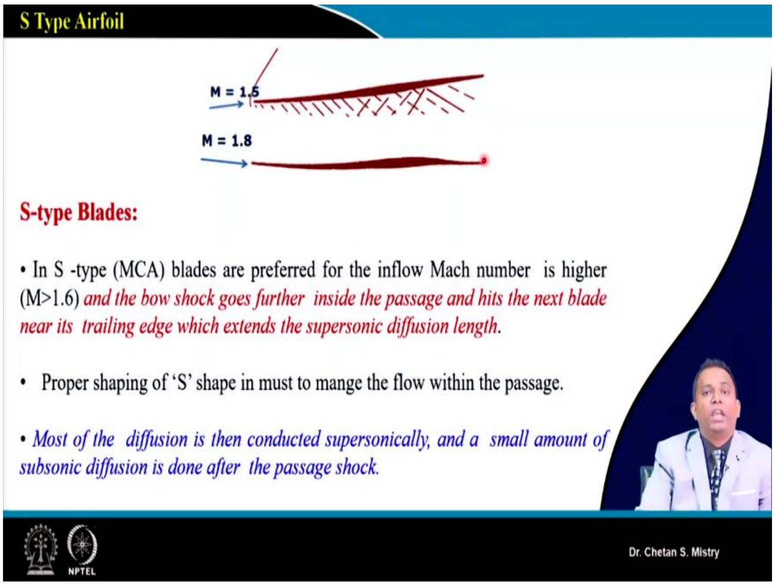

Now, next kind of blade, that's what people they thought of that's what is say S type or shallow S type of blade. So, here if you look at, this is what is representing my Multiple Circular Arc airfoil. Similar to that, here this say S type airfoil, that's what has been generated. So, here, this is what is nearly straight line, we will be having curvature here and this is what is my trailing edge, okay. When we are having say Mach number to be in high range, maybe 1.6 or 1.8, this kind of airfoil, that's what is being used.

And here, the flow management, that's what is very important. So, most of the diffusion, that's what is happening to be a supersonic diffusion and in later part, we will be having subsonic diffusion.

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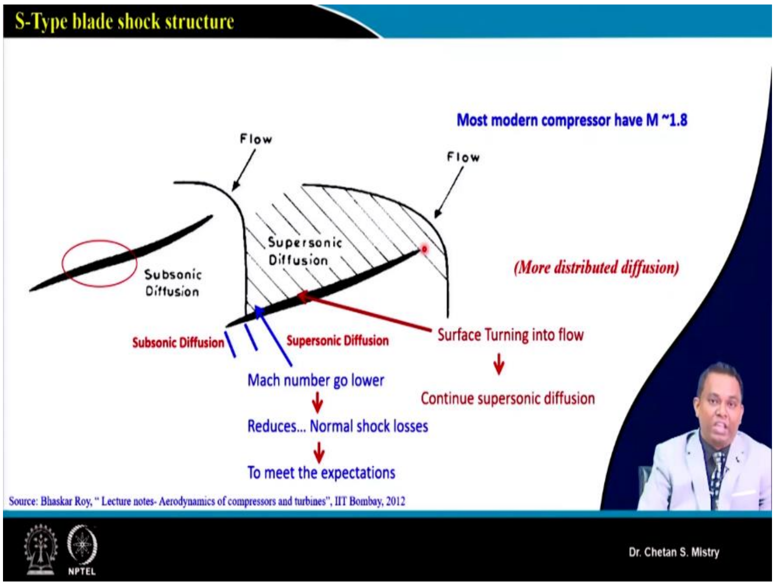

So, let us try to understand what exactly is happening. So, here in this case, as we have discussed, say this is what is nearly straight line kind of situation, and this is what is having curvature. So, when we are having our flow to be high supersonic, maybe in the range of 1.8, what will happen? Here also, we will be having the shock structure, that's what will be like oblique shock.

And here, in this case, one of the leg for that shock, it will be striking on say suction surface of say next coming blade. So, whole lot of diffusing, that's what is happening on my suction surface, only small region, that's what is giving me subsonic diffusion. And, this is what is our requirement for the future blades. So, whole lot of research and development activity, that's what has been going on for the development of such kind of airfoils for future need.

And, one important observation we need to realize here, what all blades we are looking at, if we compare my thickness of the blade, that's what is very low; compared to our subsonic airfoils the thickness of the supersonic airfoils they are low. So, basically these blades are thin blades. Now, if you recall in last lecture, we were discussing about the difference between subsonic and supersonic airfoils. There we were discussing about say thin airfoils. So, just realize what is the meaning of thin airfoil then we were discussing about the shape of leading edge, that's what is say slightly rounded or we can say not exactly the sharp one, okay.

Then we were discussing about say our stall margin. So, here in this case, the margin for stall, that's what will be less when we are discussing about the transonic airfoils. So, you can say my flow incidence, that's what is my leading edge very sensitive to the change of incidence. We will be discussing all these terms again in detail also, okay. Now, here in this case, we have seen, we are having say steeper kind of characteristic. So, this steeper characteristic, that’s what has come because of this particular shape of airfoil.

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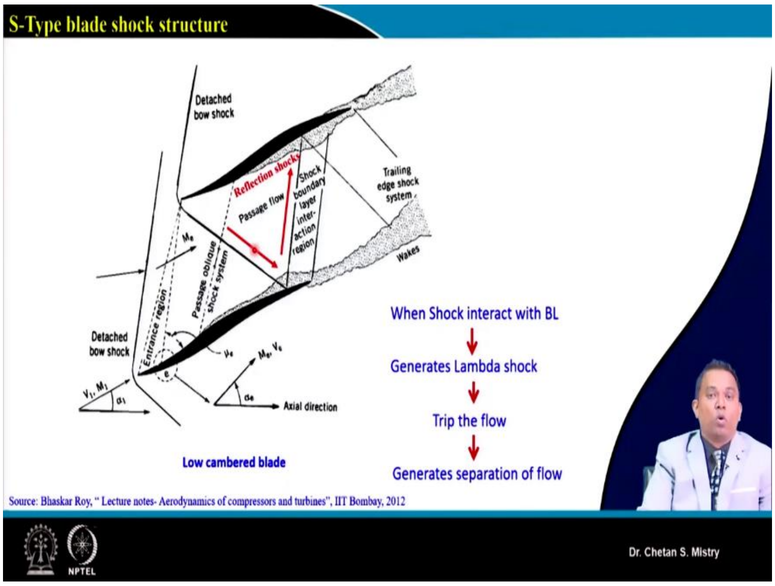

Now, this is what is a computational study, that’s what is say of need and this is what is recent ongoing research activities, we can say this is what is say my S type of airfoil. And this is what is our detached shock, because we are having our say leading edge to be slightly rounded. And that is the reason why this detached shock, that’s what has been formed.

Here, in this case, this shock that will be striking somewhere here, that’s what we have discussed. And in this passage, we will be having continuous oblique shock formation, that’s what will be going on, okay. Now, when this shock, that will be striking on my suction surface, it will be getting reflected, and again, it will be striking on the pressure surface, and then again it is getting reflected back.

Now, very important phenomena, that’s what is happening, what we know? When we are having our flow, that’s what is working under adverse pressure gradient, we will be having the separation of the flow, that’s what is one phenomenon. We know when we are having our solid body to be present, under the presence of this solid body we will be having growth of boundary layer. Now, here in this case, what will happen, when the shock that will be striking on the suction surface, because of growth of boundary layer, and the striking of this particular shock, we will be having, here, lambda shaped shock formation, that’s what will be happening.

This course is not about the aerodynamics, that is the reason why we will not be discussing in detail, but literature…open literature, that’s what is available for say supersonic compressor, S type of airfoil, how people they are realizing the formation of lambda shock and all those stuffs, that’s what is available, just go through that literature.

And, you know, when we are having this shock boundary layer interaction, we will be having the trip of flow and that’s what will lead to formation of Wake. And in later part if you look at, near say my trailing edge, we will be having thicker Wake that will be coming out and we know this is what is aerodynamic penalty, we can this is what will lead to say profile losses. So, we need to be very careful in sense of understanding of flow behavior.

So, you know, when we are doing our development of airfoil, we need to take all these parameters to be under consideration. And we need to be very careful say what condition we are designing for; and if that condition, it will go off design, under that condition, you know, this will work worst and that’s what will lead to have very high losses. Losses is one thing, but as we have discussed, when we are having say formation of…say…surge, that’s what will be happening, then the whole compressor, it will go under surge, and that’s what will lead to failure on the engine.

So, we need to be careful about all these aspects. So, if we are doing our design of supersonic airfoil, using your computational tool, it is possible to understand all these phenomena. So, people those who are well experienced, well matured and having very good understanding of this shock formation and gas dynamics, aerodynamics, they people they are putting their whole lot of efforts for the development of future airfoils.

So, here we are stopping with. We will be discussing more what all that’s what is happening within the flow passage in next lecture. Thank you, thank you very much for your kind attention.