Aerodynamic Design of Axial Flow Compressors & Fans
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Lecture 52
Transonic Compressors (Contd.)

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Hello, and welcome to lecture 52. We are discussing about Transonic Compressors.

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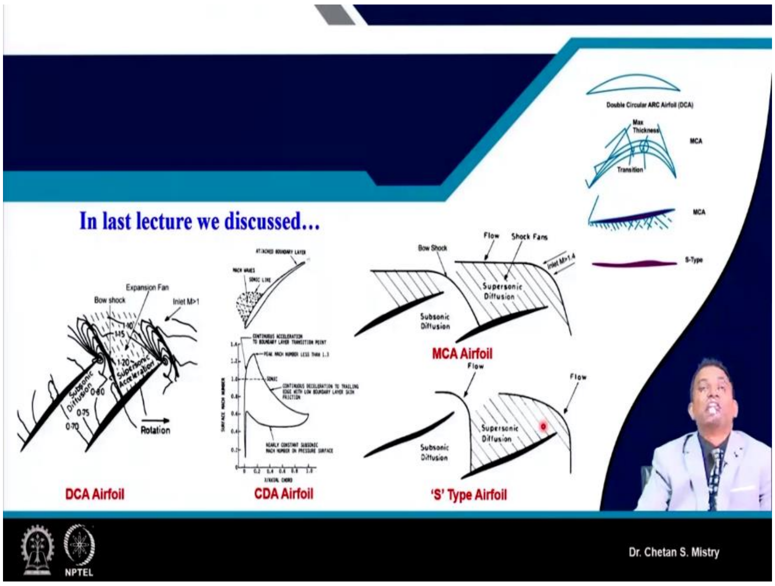

So, in last lecture, we were discussing about different kinds of airfoil which have been used for transonic compressors, named say maybe Double Circular Arc airfoil, Controlled Diffusion

Airfoil, Multiple Circular Arc airfoil, S type of airfoil. Now, in last lecture we were discussing about how the flow, that's what will be behaving, when we are using such kind of airfoils.

So, what we have observed? Say, when we are discussing about Double Circular Arc airfoil, it says, this is what is a kind of airfoil what we are using, when we are having flow, that's what is in the range of nearly Mach number of 1.4 or less than that; under that condition, when it will be striking on the blade, because of say rounded leading edge, we will be having bow shock, that's what will be formed.

So, the use of rounded airfoil, that's what we have realized now, we are not interested in making sharp edge airfoils. Let it be Multiple Circular Arc airfoil, let it be S type of airfoil, we will be having our leading edge and trailing edge to be slightly rounded, okay.

Now, for Double Circular Arc airfoil what we have observed, because of the curvature of my suction surface, downside of my shock; so, we will be having two shock kind of formation. First, that's what is initially been striking on the blade.

And second shock, that's what will be forming within the flow passage, we can say as a passage shock. So, because of curvature of our suction surface, we will be having expansion fans, which will be formed. And when my flow, that's what will be reaching to passage shock or near to location or passage shock, we will be having Mach number nearly same as what it was at the entry of my flow means entry Mach number.

And from there, because of presence of this normal shock, we will be having downside flow to be subsonic flow. So, here in this case, we will be having supersonic expansion, that's what we can say equivalent to supersonic diffusion and subsonic diffusion, that's what is happening. So, during 70s - 80s, this is what was working fine. And, that's what was mostly been used, even as on today for many fans and compressors people they are using Double Circular Arc airfoil.

Then we have seen, in order to have systematic management of the flow, in sense of formation of shock on the blade surface using computational tool, this diffusion control airfoil, they are been developed. So, here in this case, we will be having whole lot of acceleration, that's what will be happening on the suction surface in the range of Mach number nearly 1.3. And then after we will be having smooth diffusion, that's what will be happening on the later part.

And, my Mach number or my flow, that's what will be remaining nearly constant on my pressure surface. And this is what was giving very good flow behavior as per the expectation. And, these blades we have discussed, they are wide chord airfoils and they are having say some special applications.

Now, moving to the next, we were discussing about the Multiple Circular Arc airfoil, the difference here is rather having two circular arcs, we will be having four circular arcs. And, maximum thickness location, that's what is in our control, we can move forward towards the leading edge or maybe towards the trailing edge. And, that's what will be helping us in sense of managing the flow on the suction surface of the blade.

And, that's what we have seen here. Because since this is what is say we are having the suction surface shape such a way that rather than having the expansion fans, we will be having say, you know, shock fans, that's what will be forming on the surface. And, that's what was giving supersonic diffusion, and that's what was followed by subsonic diffusion.

So, when we are having Mach number above 1.4, rather using Double Circular Arc, we are going with Multiple Circular Arc. Even going crazy, if we are having say inlet Mach number in the range of 1.8 or 2, we can go with this kind of airfoil, that's what is say S type airfoil. If we compare this, we can say when our blades are highly staggered, under that condition, this kind of airfoil straight way can be used. Most of the diffusion in S type airfoil, that's what is happening, because of supersonic diffusion, and only small portion, that's what is responsible for the subsonic diffusion.

So, we can say, we are able to achieve very high pressure rise by using such kind of airfoils. Now, in the case of Double Circular Arc, we can say it is a jump diffusion kind of configuration. Here, we are having systematically management of my shock, and that's what is giving systematic distribution of my diffusion.

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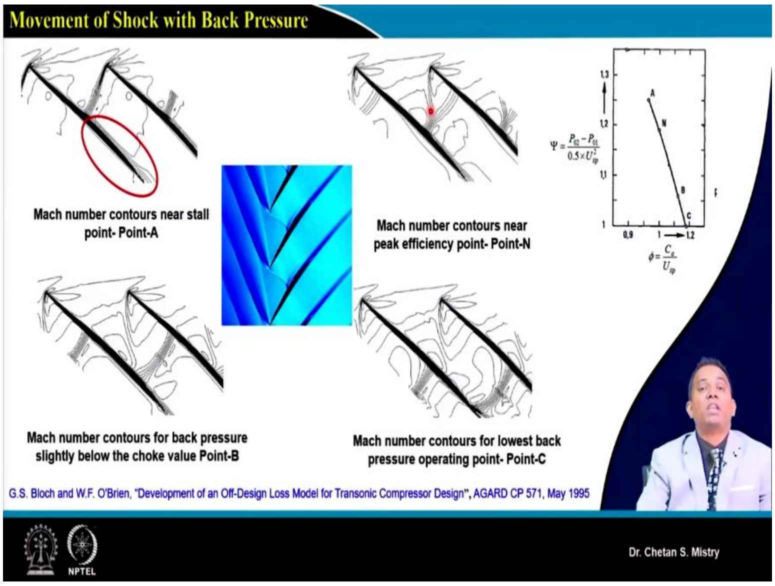

Now, with this, let us move ahead in sense of understanding what exactly is happening, when we are using that for the testing purpose, or when we are having this compressor, that's what is working. So, if you recall, this is what is representing the performance map of single stage transonic compressor, where this point N, that's what is representing my design condition. So, you know like, this is what is say maximum peak efficiency condition. Point A, that's what is representing nearly stall condition. Point B, that's what is representing choke condition. And we can say, point C, that's what is having say lower back pressure configuration. So, this is what is being reported by Bloch and O'Brien.

So, here in this case, if we try to look at what is happening in sense of shock formation within the blade passage; let us see, suppose say we are considering peak efficiency point. So, here in this case, we are having this is what we can say the passage shock, that's what will be forming. Somewhere here, we will be having normal shock. And, that's what was giving, say…considerably high pressure rise, that's what we are expecting, and we are having peak efficiency, the peak efficiency is because we are having minimization of the loss, that's what is happening.

Now here, in this case, if we move towards point A, we will be having this oblique shock, that's what will be striking here. And, that's what will be giving, say you know, nearly stall condition. Here, it is interesting to observe, if we look at carefully, this particular region, since this is what is my normal shock, downside, I will be having sudden change of pressure, and that's what will be giving adverse pressure gradient. So, there may be chances of my flow to get separated. So, by changing small mass flow rate, it may possible that my airfoil will go stall, okay.

Now, in the case of point B, we can see this shock, that's what is moving downside towards the trailing edge. So, here somewhere, we will be having the flow, that's what is getting chocked under this kind of mass flow configuration. Small change of my mass flow rate or change of back pressure, it may be possible that the shock will be standing exactly at the trailing edge and there is no further increase of mass flow rate, that's what is possible.

So, we can say, like not only we need to focus when we are discussing for the development of such airfoil. For design condition, we also need to think what flow phenomenon, that's what is happening when we are going under stall condition or when we are going for choke condition, because that's what is limiting our performance and operating range.

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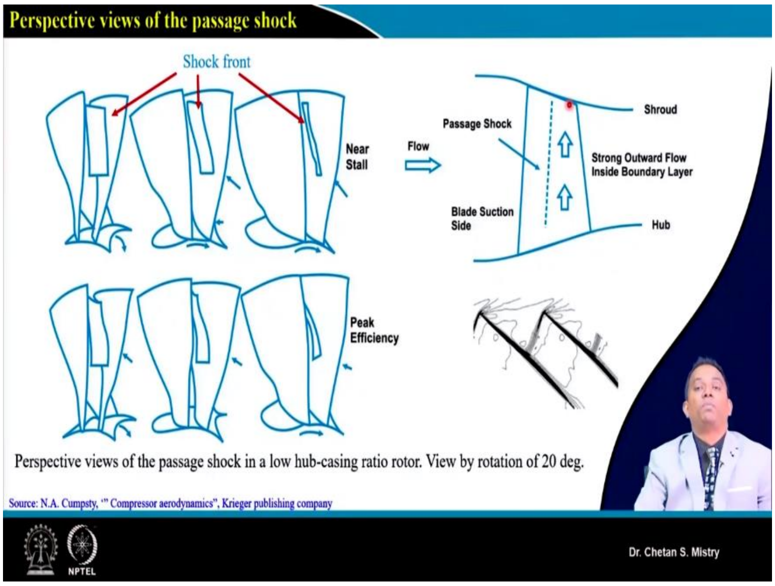

Now, in order to understand, say…how exactly my shock front that will be standing; so, because of ability of flow visualization techniques, PIV, some of the experiments and their results, they have been reported here. So, these are say low hub-casing ratio rotor. So, this is what has been tilted at say 20° interval in order to realize the shock front. So, here you can say, this is what is under near stall condition; we can say, above around say 40% percent of my span, we will be having shock front, that's what will be forming. This is what is exact location when we are tilting at 20°.

Now, what happens when we are having say peak efficiency configuration; under that condition as we have discussed earlier also in last slide, say what happens; we will be having the movement of the shock towards the trailing edge. So, we can see here, this is what is representing the moment of our shock towards the trailing edge.

Now, if we look at carefully under this what exactly is happening. So, suppose say this is what we have discussed. Say, this is what is nearly stall condition. What happens? we will be having our normal shock that will be standing here, in later part we will be having say flow separation or say presence of low momentum fluid downside.

Now, this what is happening, if we look at for say overall blades, say this is what is my transonic compressor blade. So, this is what is a location where we will be having passage shock. And, this, what we say in sense of formation of separation, that’s what will be goring say strong outward flow in the boundary layer, that’s what will be moving towards the upside. So, this is what is representing the moment of my flow on upward side.

So, this is what will be creating trouble near my tip region, we can realize, we are having the differential pressure on pressure surface and suction surface, that’s what will be giving my tip leakage flow; along with that we are having shock flow and that’s what will be creating whole lot of trouble to the flow in the tip region, okay.

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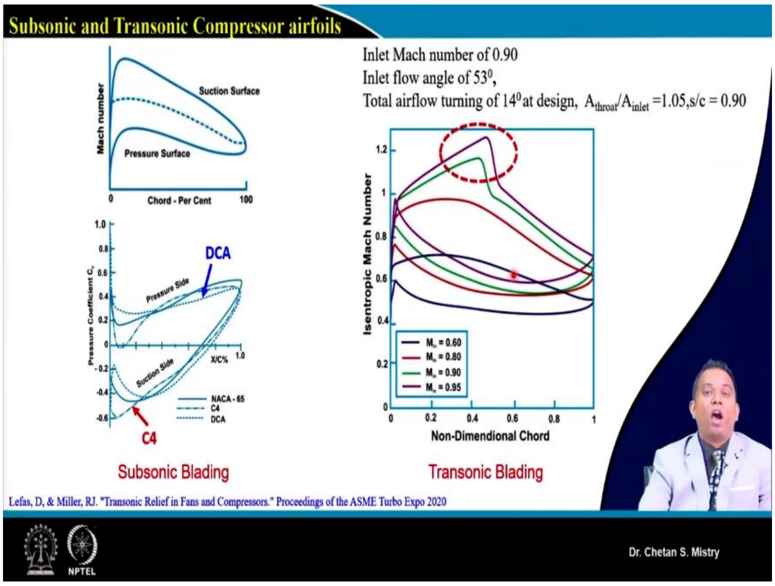

Now, let us try to look at what all we have learned in sense of our subsonic airfoil and supersonic airfoil. Let us try to understand how by flow parameters, that’s what will be affecting my flow behavior within the blade passage. So, here, if you recall, this is what is representing my Mach number distribution on the cascade…subsonic cascade. Subsonic cascade, we can say it is say C4 airfoil or maybe DCA airfoil or say NACA 65 airfoil. What is happening? We are having the acceleration of flow, that’s what will be happening from 5 to

10%, where we will be having maximum acceleration and thereafter, we will be having the deceleration of flow, that’s what is happening on the suction surface.

And, we can say on pressure surface, we will be having the acceleration of flow and later on it will subjected to say flow deceleration. And, this area under this curve, that’s what is representing my pressure rising capacity of this particular airfoil.

Now, suppose if we consider, we are having say transonic airfoil. Say here, this work, it has been reported by Cambridge University, Professor Miller, what they have done, they have taken say transonic airfoil, which is been having say inlet Mach number of 0.9, the inlet flow angle is 53°, say flow turning angle is 14 and area ratio, we will discuss very soon, throat area to inlet area is 1.05 and say pitch to chord ratio is 0.9.

Now, when this airfoil is subjected to different inflow conditions, suppose if you consider say varying the Mach number 0.6, 0.8, 0.9, 0.95. So, here if you look at, since this is what is airfoil, that’s what is say transonic airfoil and our inflow condition is say, you know, subsonic kind of configuration, we can say this is what is representing what is happening on my blade suction surface and pressure surface when my Mach number is 0.6.

When, I am increasing my inflow Mach number, we can see, we will be having say acceleration of flow, that’s what will be happening on my suction surface nearly up to say 40% of my span. And, then after, this is what is represent the formation of shock and later on we will be having the deceleration of the flow, that’s what is happening on my suction surface. Same way we can say, this is what is happening with our say pressure surface we will be having the acceleration of flow and in later part, we will be having the deceleration of flow, that’s what is happening on my pressure surface.

So, the meaning is what we are looking for at this moment is suppose if you are having our airfoil to be transonic airfoil and if it is subjected to say subsonic inflow condition and say maybe designed condition, how my flow that will be behaving, okay.

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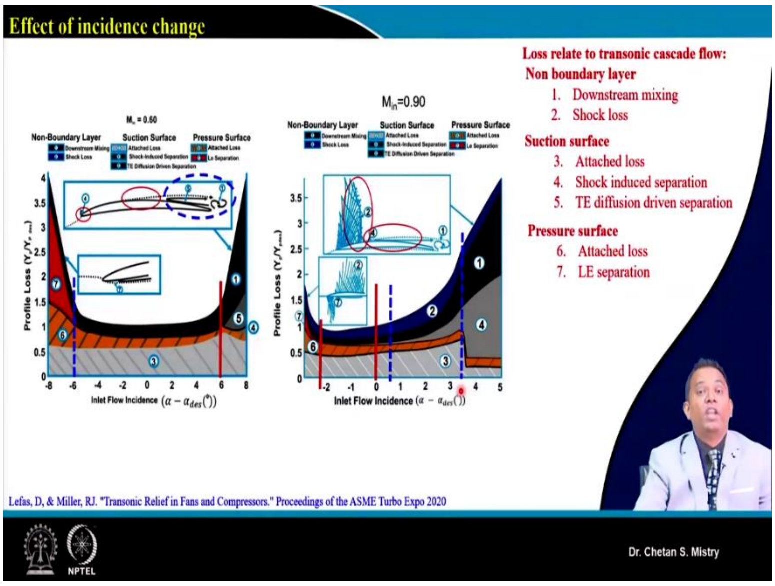

Now, in order to realize that part, let us see this is what is very interesting plot, that’s what is representing, what is the effect of change of incidence angle. So, this is what is representing when we are having say our inflow condition or inflow Mach number to be 0.6. And this is what is when we are having inflow Mach number to be 0.9. Now, in order to distribute the losses, say…Professor Miller, they have divided the losses in different categories, they have divided in sense of non boundary layer kind of losses, suction surface losses, pressure surface losses.

Now, in case of non boundary layer kind of losses, it says like downstream mixing losses, we can say what is happening towards the trailing edge that’s what we can say as downstream mixing losses, we are having shock losses, we are having attached loss, shock induced separation, trailing edge diffusion driven separation. On pressure surface, we will be having attached loss and leading edge separation loss.

So, let us try to realize what is happening when we are having our inlet Mach number to be 0.6. Now, here in this case, if we look at, this is what is a particular region when we are having our incidence angle, that’s what is positive. Do not forget when we say our incidence angle is positive means my flow that will be striking towards the pressure surface. Now, if that’s what is your case, what is happening here? If you look at carefully, in this particular region near our suction surface, we will be having flow acceleration, that’s what will be happening.

So, here in this case, we will be having shock formation, that’s what will be happening, okay. Now, since this is what has been formed, we can say this is what is say location 4, that’s what is called say shock induced separation. Because we are having this, you know, separation, that's what will be forming because of this acceleration, what it will be doing, it will be moving towards the downside.

So, in this particular region, we will be having the flow separation, that's what will be happening, okay. Now, because of this flow separation, in downside direction, we will be having our mixing loss, that's what will be going to be increased. We will be having thicker wake, that's what will be coming out. So, we can see, in this region we are having say trailing edge diffusion driven separation, and we are having say downstream mixing losses, that's what is going to boost up. So, we can say this is what is representing my mixing losses, this is what is representing my diffusion driven say separation. And this is what is say shock induced separation, that's what is happening.

So, we can say when our flow is subsonic and our incidence angle, that's what is say positive, this is what will be giving rise to the losses. Now, towards say negative incidence side, suppose if we look at say my angle to be $-6°$, what happen? So here, in this case, when we say it is a negative incidence angle, my flow that's what will be striking towards my suction surface and that's what will lead to give my leading edge separation.

So here, we will be having leading edge separation. You can say, with increase of incidence this leading edge separation losses, that's what is going to be increased, okay. Now, you know, this is what is representing when we are having our airfoil to be transonic and it is subjected to subsonic flow or subsonic in flow condition.

Suppose, if I consider say for the same airfoil, my inflow Mach number is say 0.9. Suppose, if we look at say, we are having zero incidence case. So, even for zero incidence case, we are having the presence of shock losses, you can see here. What is happening when we are having zero incidence? I will be having whole lot of acceleration that's what will be happening on my blade surface and that's what will be subjected to have say shock losses.

So, here we are having shock losses, that's what will be forming. If we are moving slightly downside, maybe, if you are changing this say incidence angle say 0.58, under that condition, we will be having suction surface separation, that's what will be happening in this particular region, okay. When we are moving towards the downside, suppose say incidence angle in the range of say maybe 3.3; under that condition, we will be getting some different kinds of flow physics, okay.

Here, in this case, we will be having shock induced separation, that's what will be very large. We will be having say downstream mixing losses also will be very large and we will be having shock losses. So, we can say my losses, that's what is going to increase when we are having our incidence angle in the range of maybe 3.2 or 3.3.

Now, towards the negative incidence direction if we are going here, say, maybe around maybe incidence angle of minus 2.2 or 2.4; under that condition, if you try to look at, we are having this is what we can say is…say…my shock losses. So, shock losses, we can see, this is what is my blue color one, and because of I am having negative incidence, we will be having the formation of shock here, that's what will lead to give say leading edge separation. And, that's what is increasing my losses. So, when we are comparing these two, for low subsonic Mach number or say subsonic Mach number of 0.6 and Mach number of 0.9, we can say our operating range, it is very sensitive, just look at the numbers.

So, here we can say, we are having the losses to be rising for say incidence angle of 6. Here, in this case, when we are talking about the transonic airfoil, my this incidence angle, which will lead to give more losses, that will be in the range of maybe 3.2 to 3.5, okay. So, we need to be very careful, that is the reason why we are saying when we are using our subsonic airfoils for supersonic flow or supersonic airfoil for subsonic flow, we need to be very careful, we need to catch an eye for all kinds of loss formation, that's what is happening, okay.

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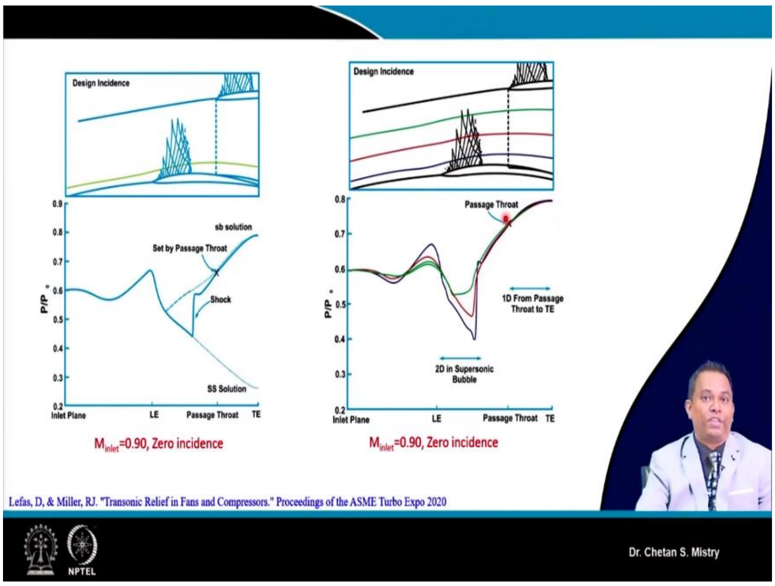

Now, let us try to move and try to understand what exactly is happening within the blade passage. So, here if you look at, these are the two airfoils they are being arranged in a stream tube configuration. Here, if you look at, this is what is representing my say as acceleration of the flow on suction surface, that's what will be having say end with the normal shock here. So, you know, this is what is representing for the variation of pressure for this particular streamline.

We can say in pitch wise direction, we are selecting one of the streamline. So, this is what is one of my streamline. If we are putting or we are tracing, what is happening with the pressure, you can see this is what is representing the variation of pressure. Now, in the case when we are having say presence of this blade, we can say, we will be having the deceleration of the flow, that's what is happening, that's what will lead to have say rise of pressure ahead of our leading edge.

Now, since we are having the acceleration of the flow, that's what is happening on say suction surface, that's what will lead to reduce my pressure. So, this is what is representing reduction in the pressure. Somewhere here, we are having normal shock and this is what has been representing sudden rise of pressure; we can say this is what is sudden rise of pressure. And, later on this particular region, that's what is subjected to we can say, when we are having subsonic diffusion. So, this is what is representing my subsonic diffusion.

Now, this dotted line what we have taken, that's what is when we are considering our flow to be completely subsonic and when we are considering our flow to be completely supersonic. Say, this is what is with say subsonic entry of 0.9. So, when we are considering low subsonic configuration, and when we are considering supersonic range, maybe Mach 1.2-1.3, this is what is representing, okay.

And, somewhere here, we will be having the interaction of this say subsonic solution and this is what is for this particular location, that's what will give the location for the throat. So, this is what is representing the location of my throat. We can say throat definition, that's what is seen here, that is where we are having minimum area.

Now, let us move ahead with the same kind of configuration rather having one streamline, let us take three different streamlines. So here, this is what is say near to my suction surface, this is what is nearly at the mid station and this is what is towards my pressure surface of other blade.

So, here in this case, if we try to look at, this is what is representing what is happening with my pressure distribution. So, now, for green, for red line and for this blue line, this is what is happening. Now, if you try to look at here, since this is what is more towards the acceleration region, and that is the reason why we are having more acceleration, that’s what is happening here. Comparatively less acceleration, that’s what will be happening here for the second streamline.

And here, if you look at, this is what is not coming in say acceleration region, and that’s the reason why this is what is not subjected to any kind of shock formation. So, this is what is say, you know, continuous kind of flow in sense of diffusion, that’s what is happening.

For all the three lines, if we look at carefully, this particular region, where we are having throat to be placed. So, we can say our throat, that’s what is at the common location. Now, this is what is representing what is happening when we are having our design configuration and zero incidence case.

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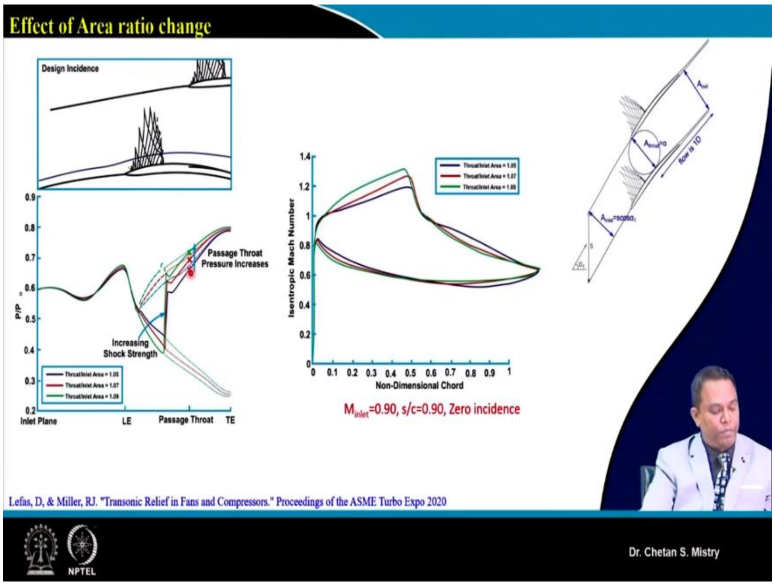

Let us try to look at what is happening with the change of area ratio. So, what we mean by area ratio is, you know, here in this case, we can say somewhere here, we are putting this as my inlet area, this is what is representing my minimum area we can say is the throat area, and this is what is the exit area.

So, for this airfoil, design area or design area ratio is 1.05. So, this is what is representing what is happening with our isentropic Mach number. So, if you look at carefully, if you are changing our throat area, the location of my shock, that’s what is changing, and we are having different configuration of the acceleration, that’s what is happening on the suction surface. So, if we try to look at here, suppose, if we consider say three different area ratio, and if you are putting together, say for the area ratio of 1.05, this is what is representing in sense of what is happening with the normal shock. And we can say this is what is representing the strength of my shock, okay.

When I am increasing my throat area, this rise of pressure, that’s what is going to be large. And, that’s what is showing, like the strength of my shock, that’s what is going to increase. And, you know, our location, that’s what is say my throat location, that’s what is coming at the same place, but that location or say the placement, that’s what is somewhat different.

So, we can realize, how we are managing our flow by changing the area ratio. So, this is also one of the possibility. Do not get confused when we say we are changing area ratio in order to manage the flow, maybe small change in sense of thickness or maybe change of say location of maximum thickness, that’s what will be helping or maybe we are changing the movement of our curve, camber line, that’s what will be helping in order to achieve the change of this throat area.

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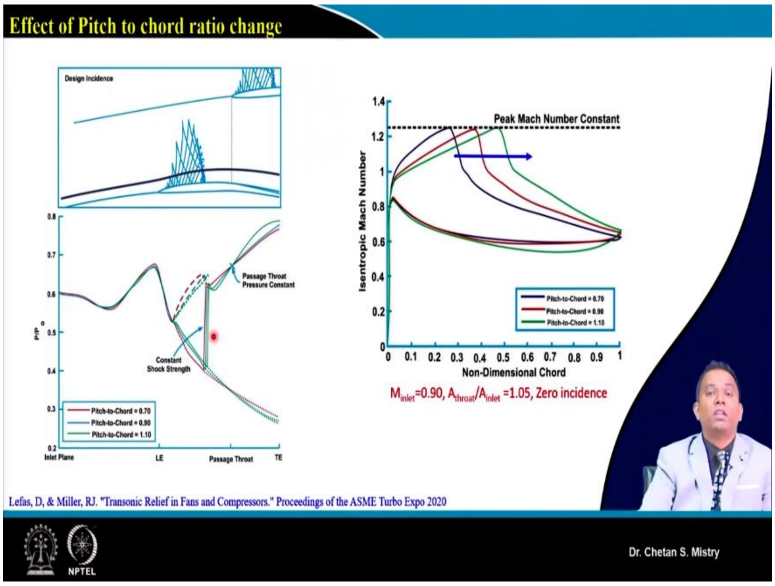

Now, next case, that’s what will be coming is in sense of change of say pitch to chord ratio. We must realize here, we can say, this is what is in line to what we are discussing in sense of say number of blades. So, you know, change of this pitch ratio that is also having considerable effect on say the flow configuration. So here in this case, if we look at, say this are say…different…say…different pitch to chord ratios. So, design pitch to chord ratio is 0.9 and we have reduced to 0.7 and say maybe 1.1.

If you look at the peak Mach number, that’s what will remain same, only the location of my normal shock, that’s what will be going to change. So here in this case, if you are comparing, so it says, like when we are having say different pitch to chord ratio, we will be having the location, that's what is going to change, okay. And, this is what is changing the strength of my shock. And, that's what will be lead to change my flow parameter or flow behavior in the later stages. So, this study, that's what is very important for our study.

Now, we can say, like what all we are discussing is, we started discussing about airfoils, specially transonic airfoils. Then after we were discussing about the formation of shock, then we were discussing about how my flow, that's what will be behaving on my suction surface and on my pressure surface. Later on, by understanding of that, we need to do systematic management of our shock.

And, that is the reason why we are looking for special kind of blade surfaces. We are looking for special kind of camber lines, we are looking for arrangement of pitch to chord ratio. We are looking for what is happening with the change of incidence angle. We are looking for how the area ratio, that's what will be affecting my flow behavior.

Now, looking to all these, that's what is giving indication to us saying like, you know, how to develop all these blades? How to design these blades? How to get the coordinates for pressure surface, how to get the coordinates for suction surface? What need to be the leading edge radius, what needs to be the trailing edge radius? What need to be my camber line? What need to be my maximum thickness? So, all these things, that's what need to be known to us.

Suppose, if we know, we will be having initial simulations using the computational tool; based on say received result or what all results we are getting, do post processing. Using that post processing, try to understand how my flow is behaving in the blade passage. And as per the requirement, you can modify the shape of your blade and that's what is people they are doing.

So, in next lecture, we will be discussing about how to develop different kinds of camber lines, how to decide the thickness distribution, how do we arrange our blade as per our requirement. Thank you, thank you very much for your kind attention!