Aerodynamic Design of Axial Flow Compressors & Fans
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Lecture – 26
Cascade Aerodynamics (Contd.)

Hello, and welcome to lecture 26 for aerodynamic design of axial flow compressors and fans. We are discussing about the cascade aerodynamics.

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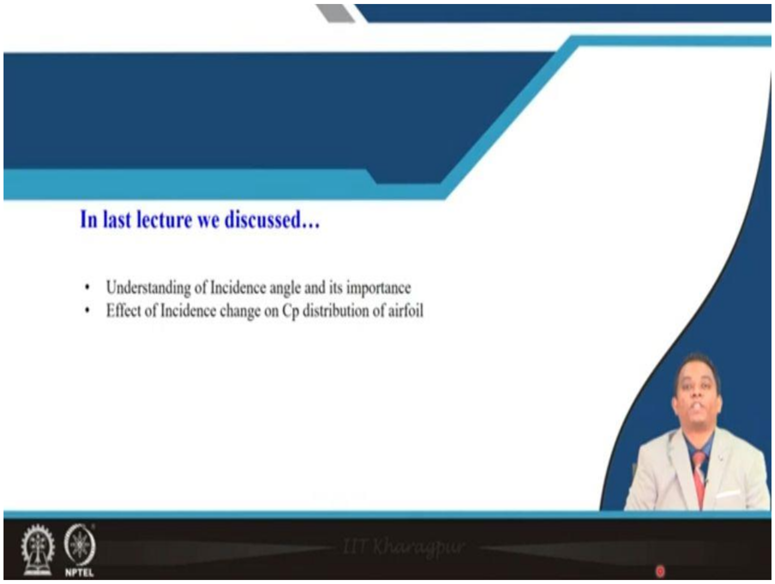

In last lecture, we started discussing about say change of incidence angle. So, we have realized what we mean by incidence angle and what all are the conditions; those are bringing the change in the incidence angle. So, if we recall, we were discussing about the change of my axial velocity, change of peripheral speed; and we have discussed using the performance map of single stage axial flow compressor. So, we realize this change of incidence that's what is happening with the change of axial velocity and change of peripheral speed.

If I say, I am decreasing my axial velocity or say I am increasing my peripheral speed, that's what will lead to give you increase of incidence angle. Now, when we say increase of incidence angle, that's what is having certain change on my flow physics on suction surface of the blade. In line to that we started discussing about what all will be the change in the C_p distribution.

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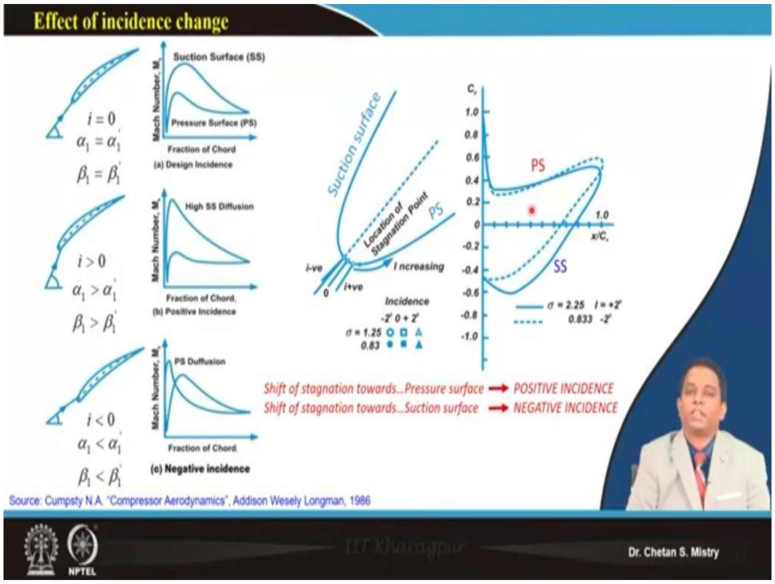

So, let us move what we have started discussing in last lecture. So here, these three conditions we have discussed. We have started discussing say…incidence angle equal to 0. We were discussing about say increase of incidence angle or what we say as positive incidence angle; we were discussing about the negative incidence angle. And if you look at these three; that's what is representing how my surface Mach number that's what is changing along my chord. And if we try to look at and if we correlate this in sense of C_p, we can say with having positive incidence angle, my Mach number distribution that's what is giving me higher pressure rise or higher C_p distribution.

Then, we started discussing about how we are defining as say positive incidence angle and how to define the negative incidence angle. That's what is based on how my stagnation point that's what is located on my leading edge. If we consider the stagnation point, that's what is located towards the pressure side; that's what we are discussing or we are saying that as positive incidence angle, when we are having our stagnation point moving towards say…suction surface; that's what we are defining as say negative incidence angle.

And here this is what we have discussed in sense of how my C_p, that's what will be changing with the change of incidence angle. Now let us move ahead.

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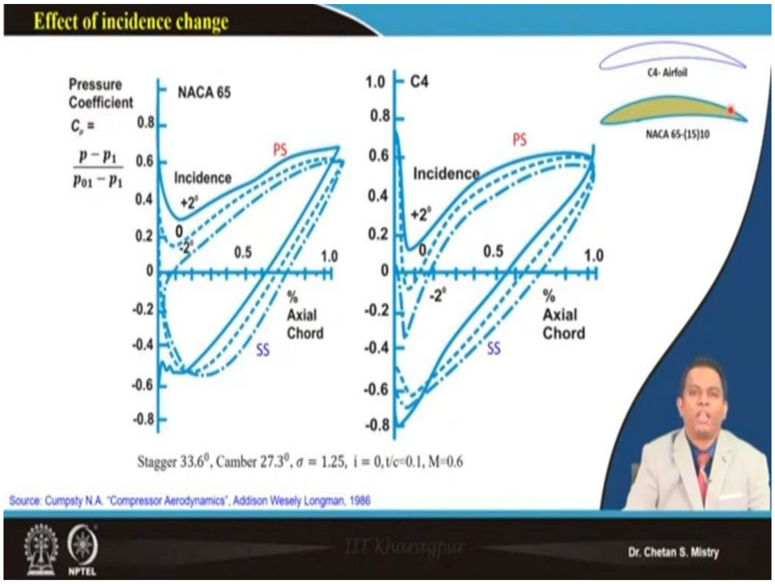

So, we know for subsonic airfoils, we are having different options available. But, mainly for say your subsonic compressor or subsonic airfoils, what we are using? They are C4 airfoil and NACA 65 airfoil. Now, if you compare the leading edge, then for C4 airfoil, my leading edge that's what is having say larger radius. And if we compare that with say NACA 65; for NACA 65, my radius of leading edge that's what is smaller. Now, this change or the shape of my leading edge, that's what has great impact on my C_p distribution. So, let us consider first say NACA 65 airfoil. So, here if you look at, this is what is representing how my C_p or pressure distribution that's what is changing along the chord for particular flow angles.

It says stagger angle is 33.6, camber angle is 27.3, and solidity that's what is say 1.25. And incidence angle, at initial stage it is 0, thickness distribution is 0.1 and Mach number that is 0.6; so, entry Mach number is 0.6. So, both the plots they have been done for this configuration. If we try to look at for say 0 incidence case, this is what is representing what is happening in sense of acceleration on my pressure surface; and later on, how the diffusion that's what is continued to happen on my pressure surface.

If we look at here near the suction surface, I will be having great acceleration; that's what is happening on the suction surface. And that too it will be continue up to say maybe 20% of my chord; and later, that's what will be giving the deceleration to my flow. So, here this dotted line if I will be putting, the area under this curve, that's what is representing my pressure rising capacity of this particular airfoil at 0 incidence angle. Now, suppose if I consider say, I have changed my incidence angle.

Now, recall as a told, this experimentation or this data that's what has been captured by using linear cascade tunnel, okay. So, here in this case, at the entry my flow angle that's what is being changed such that I will be having positive incidence angle. So, when we are having positive incidence angle, the acceleration that's what is happening on the pressure surface that's what is comparatively low. And here in this case, if we consider on suction surface, I will be having higher acceleration that's what is happening; and that's what will be giving higher pressure rise, okay. Now, in line to that if we consider for minus incidence angle, we can have our C_p distribution to be lower compared to positive and 0 incidence case.

Now, if we look at carefully, the C_p distribution for C4 airfoil, as we have discussed this is what is having say large or radius of my leading edge; or we can say, the thickness of my leading edge that's what is larger. So, that's what is reflecting what is happening on my pressure surface and suction surface. So, we will be having higher acceleration that's what is happening on the suction surface. At the same time, we are having higher acceleration that's what is happening even on my pressure surface. If you compare these two, you can clearly see the difference. Now, for this C4 airfoil, as we have discussed this is what is representing what is happening on my pressure surface, and what is happening on my suction surface.

Now, this larger radius leading edge, that's what is giving the flexibility to blade in sense of say incidence angle; that will be comparatively less sensitive to incidence angle and that's what is giving the priority. So, most of the subsonic compressors what we are observing, people at the initial stage, they are starting with say C4 airfoil or British airfoil. Many American compressors we are looking at, they are having NACA configuration that's what is there. Now, here if you look at, not only leading edge is important; at the same time, this trailing edge is also equally important. So, here if you look at, my trailing edge for C4 airfoil, if you look at that's what is having certain amount of radius, okay.

So, this is what is say having radius if we compare for NACA 65; that's what is sharp edge. So, many times in order to have fabrication, such kind of airfoils to make it will be more challenging. Because, the thickness towards the trailing edge is less; there maybe possibility that it will get damaged during the manufacturing process only. And that is the reason why people they are try to use C4 kind of airfoil at the initial iteration, okay.

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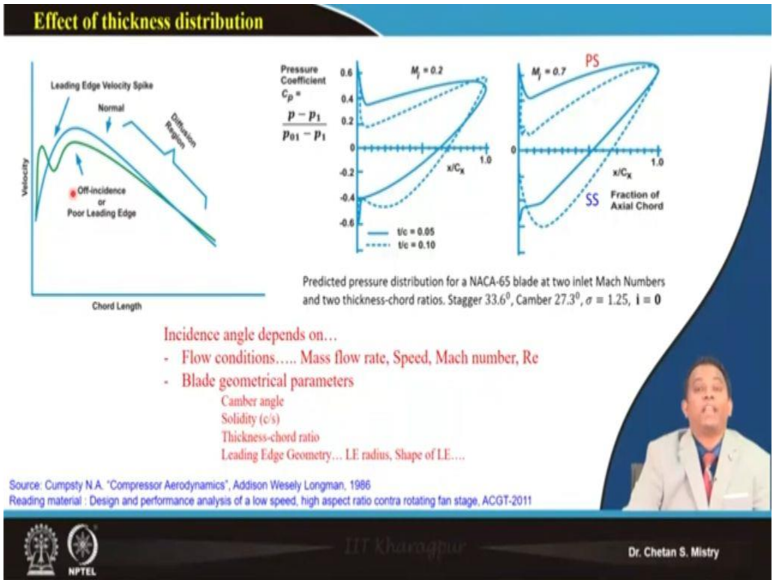

Now, let us move, let us try to understand what all are the effect of other parameters. If we consider here, this is what is representing my C_P distribution for particular kind of airfoil. If you look at, for this case, if you look at, this is what is for say NACA 65 airfoil; and that's what is having stagger angle is 33.6, camber angle is 27.3, solidity is 1.25; and this is what is say my design condition. Now, if we look at carefully, say for my entry Mach number for say 0.2; if we consider, we have used two different thickness distribution. Now, remember this is what is say thickness to chord ratio; that is nothing but the maximum thickness of my airfoil.

Here if you look at, my thickness to chord ratio is 0.05; that means, it is a 5% thickness. Suppose, if I have 100 mm chord accordingly, I will be having the thickness of say 5 mm. In line to that this is what is we are having a thickness to chord ratio of say 0.10. So, if we compare these two, this is what is giving some other kind of feeling. So, if we look at, for say thickness to chord ratio of 0.05 say on my pressure side, you will be having less acceleration and nearly constant pressure rise that's what we are getting under pressure surface. And we will be having higher acceleration that's what is happening near my say…suction surface; and this is what is representing the diffusing process.

So, this is what is representing. What is a change or what is the effect of change of thickness ratio okay. Now, next condition it says when we are having our entry Mach number to be 0.7. So, if you compare these two, it clearly says when my entry Mach number that's what is increasing; that's what is increasing my C_p or, say for a particular airfoil, my C_p distribution, that's what is changing. Now, here in this case, when we are considering Mach 0.7, on pressure surface for thickness to chord ratio or say lower thickness of 0.05, I will be having less acceleration, that's what is happening on my pressure surface and this is what is giving me my C_p distribution.

So, here, we need to realize one thing, say… when we are doing our design… say… we are doing our design based on what all parameters we are expecting. Now, from that those parameters we can calculate, we can have different calculation of different parameters or say degree of reaction, diffusion factor, different angles, how they have been varying with the change of my vortex configuration. All those that's what is giving me what will be the variation of my $\Delta\beta$ at the entry from hub to shroud, at the exit from hub to shroud.

Now, with all these data, what we need to do is these data we will be feeding for a particular kind of airfoil; because that's what is my requirement. Now, at the initial stage when we are doing our design, we need to assume or we need to select one of the airfoil for our rotor or for stator. Then, after based on what is happening on my blade surface, we need to visualize how my flow is behaving near the leading edge, and how my flow that's what is behaving on my suction surface and pressure surface. Suppose, if we consider say we are having the variation, that's what is giving say positive incidence, we can say that's what will be giving me high C_p distribution. If we are having negative incidence angle, that's what is giving different kinds of C_p distribution or say lower C_p distribution.

And based on our expected pressure rise at the exit, we need to play with different parameters. Now, those parameters we can see; one of them that's what is the play with say variation of the thickness, thickness of my airfoil. We need to remember when we are considering say thickness, it should not be too lower. If we consider our thickness to be too lower; it maybe possible that my leading edge radius will be coming to be lower. It maybe possible my trailing edge radius will be coming to be lower, because that's what is a function of thickness ratio.

Let me tell you say for leading edge, the radius roughly it is 15 to 20 % of my thickness ratio; and my trailing edge that's what is say approximately 0.5 to 0.7 of my thickness ratio. So, we can understand when we are selecting this part, or we are changing our thickness distribution, accordingly my leading edge shape, my trailing edge shape that's what will be changing. It maybe possible that my leading edge that's what will be coming very thin, like, compare… as we are comparing towards say transonic kind of airfoils or say NACA 65 kind of airfoils. Under that configuration, it will be very sensitive with the change of incidence. So, it maybe working fine for say design condition, but when we are moving towards off design condition, it may not work fine, okay.

So, it says my incidence angle, that's what is mainly been depend on my flow conditions; what flow conditions? We say, what is my mass flow rate, that's what we can say what is my axial velocity, what is my absolute velocity, what is my relative velocity. We have… it depends on what is my rotational speed of the wheel. It also depends on Mach number, our Reynolds number; now this Reynolds number that's what is very important. Here we are calculating our Reynolds number based on the chord, okay.

So, how my flow that's what is behaving on my suction surface, and how it is behaving on my pressures surface? That's what is basically it is giving us idea what is happening in sense of diffusion process, okay. This incidence angle also is depend on what is my camber angle, okay. It is depending on what is my solidity; it also depends on thickness to chord ratio. It is also depending on my leading edge geometry, mainly what is my leading edge radius, what is my trailing edge radius, okay.

Now, the question is, what is the use of this incidence angle? Let… let us discuss in a different way. Suppose say, I am making or I am designing my blade. Now, we know because of change of my parameters, say axial velocity, my peripheral speed, my incidence angle is going to change.

So, if we consider, say…we are having say our incidence angle when my axial velocity is decreasing, that means I will be going with the positive incidence angle, okay. And, that's what will be giving me high pressure rise. Now, when we are doing our design, what these designers are doing? At the initial stage only, they are assuming some incidence angle, yes. Suppose, if we consider near the hub, they are assuming this to be say positive incidence angle; near the tip, they are assuming negative incidence angle. Now, when I say positive incidence angle near the hub and negative incidence angle near the tip region; you can say with the change of my axial velocity that's what will be working under still design condition.

Just remember, suppose say, I am changing my axial velocity; that's what is increasing my incidence angle. But, by default we have given negative incidence angle near the tip region, so, that's what will lead to, you know, work under design condition, even though it is working under off design condition. We will be discussing this when we will be discussing with the design aspects, okay; this is very important. Now, onwards what angles we are defining that's what will be define based on blade metal angle or blade manufacturing angle.

So, what blades we are looking at those blades are being designed, and they are being fabricated by considering the change of incidence angle. Suppose, if I consider I am having my air angle that's what is known to me; β that's what is say β_1 *and* β_2. Mainly, β_1 that's what is known to me, I will be incorporating my incidence angle there. And based on that, I will be making my blades, okay. So, this is what is very tricky, okay. So, we need to remember what is happening with the change of incidence angle. Here this is what is something different that's what we need to realize. Here, if you look at, if we are having some change in the shape of leading edge; as I told, my incidence angle, that's what is very sensitive with the shape of my leading edge.

So, it is supposed to work in a normal condition like this. So, this is what is my normal working condition. And this is what is my region where my diffusion, that's what is happening. Now, because of some change in the geometry at the leading edge; that maybe because of fabrication error, that maybe because of deposition of foreign particles, that maybe because of say striking of my bird or striking of say foreign object. What it will be doing? It will be modifying the shape of the leading edge. And when it is modifying the shape of my leading edge, you can say this is what is working under off design condition, okay.

So, we need to be very careful for the shape of the leading edge for our compressor, okay. Now, let us move towards the next understanding.

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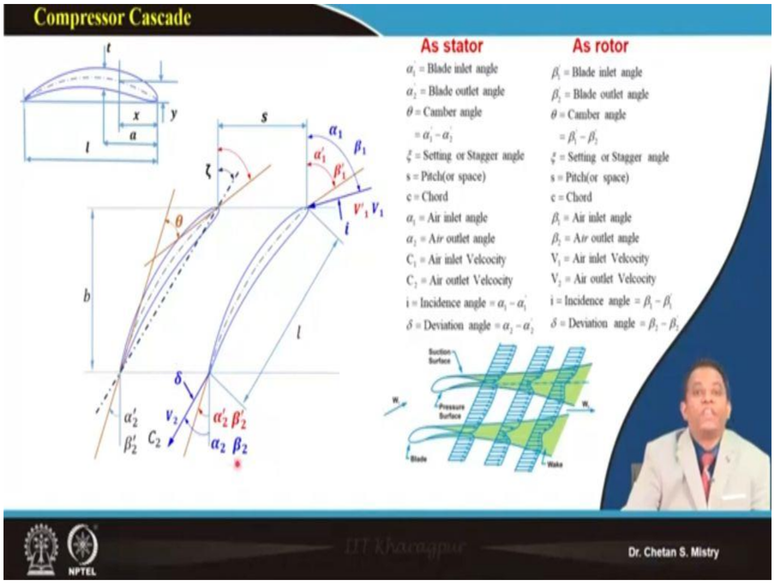

Here, in this case you can understand at the entry, we have discussed what we say in sense of incidence angle. Now, second important parameter for us to consider, that’s what we say is a deviation angle. Now, this deviation angle, we have discussed earlier also. What we realized because of presence of low momentum fluid, because of growth of boundary layer; and since my blade or my airfoil that’s what is working under adverse pressure gradient. You will be having the flow, that’s what is moving away from the trailing edge.

And that’s what we have defined as say wake, that will be coming out at the exit. And, the difference of my angle, that’s what we have defined as a deviation angle. Now, this deviation angle that is also equally important, okay.

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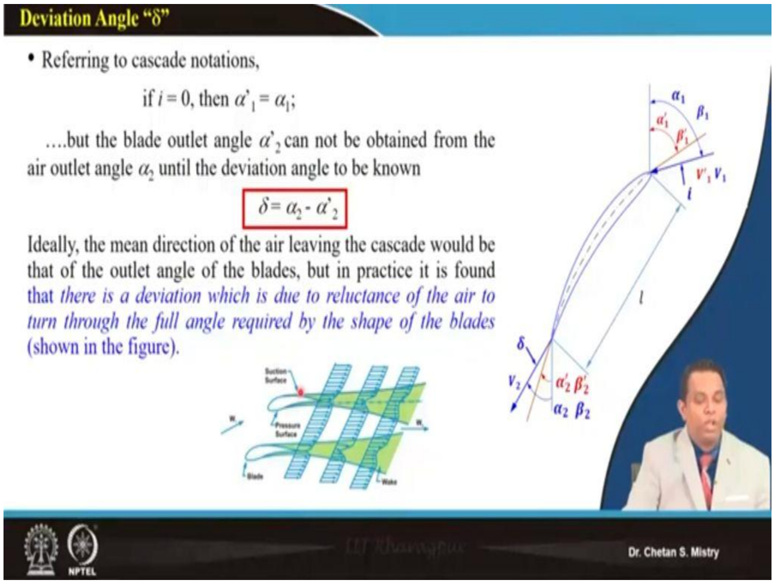

So, let us try to look at what we have realized. So here in this case, this is what we have discussed about say our deviation angle; this is what we have defined as a deviation angle. Suppose, if I consider, I am having my incidence angle to be 0, that's what is say my design condition; but still, my deviation angle can never be 0. This is what is because of my inherent property of the airfoil. This is because of what we say what is happening on my suction surface of the airfoil. What it says? This is what is because of, you know, my flow that's what is reluctant on the shape of my blade, okay. So, here if you look at, this is what is a region, where I cannot avoid such kind of situation.

And that's what it is lead to give, by default this deviation angle. So, deviation, that's what is prone to happen when we are talking about the airfoil, okay.

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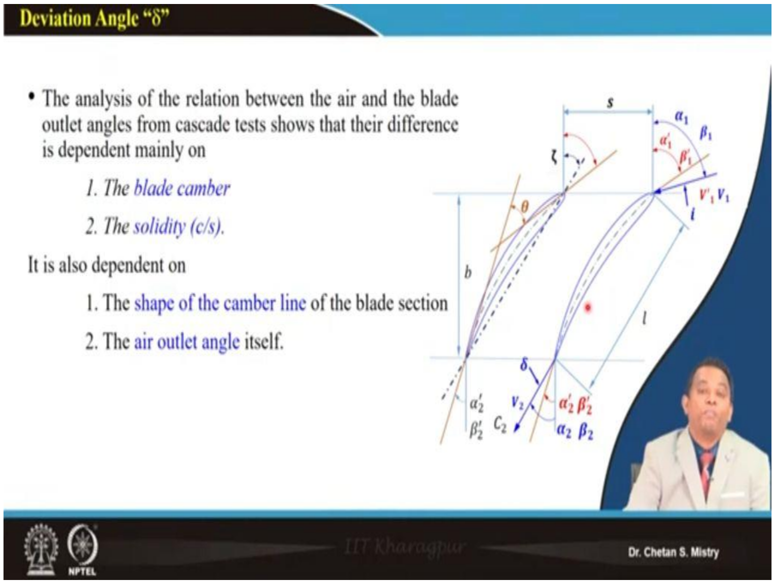

Now, in order to understand what we have realized about this deviation angle; what it says like this deviation angle, that's what is mainly been depend on different parameters. The parameters are say… blade camber; we will see how that's what is changing, okay. Second, that's what is my solidity? We can say what is my chord to pitch ratio. It is also depend on what is the shape of my camber line. Yes, this is also very important and what will be my outlet flow angle, okay. Now, here in this case, if you look at carefully, suppose if we say… this is what is my deviation angle. If we look at my camber angle, suppose say if this is what is my camber angle; suppose say I will be having my camber angle to be large.

So, you can say this angle, it is increasing, that's what will lead to give my flow to be coming out at different angle. And, since we are working under adverse pressure gradient, we have realized larger will be the turning of my blade, there are more chances for my flow to get separated on the suction surface. And that's what will lead to have thicker wake that will be coming out; that means my flow it will be coming out at larger deviation angle, okay. Now, how my blades they have been set between say…we say…this is what is my pitch, okay. So, when we arrange our blade nearby, when we are arranging our blade away, that is also having the effect.

Same way, what kind of camber line what we are selecting, that is also having the effect; and what outlet angle we are deciding that also is impacting. So, let us see.

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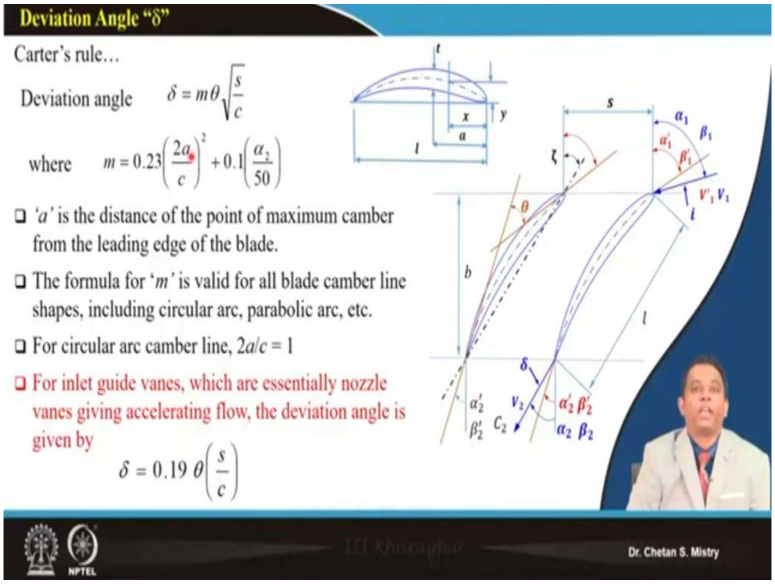

What we say in sense. So, this is what we have discussed about say calculation or say derivation for say…deviation angle. So, Carter, he has done whole lot of experimentation; and based on those experimentation on cascade tunnel, he has come up with the equation for the calculation of deviation angle. So, reported work, that's what is older work during fifties; but as on today also, as a rough calculation…first estimation of calculation, people they are using this equation, okay. So, in NASA SP 36 document as we have cited as a reference, the details that's what is available for different types of airfoil, what experimentation they have done, and how they have come up with the equation.

So, it says my deviation angle $\delta = m\,\theta\sqrt{\frac{s}{c}}$. So, as we have discussed, my deviation angle, that's what is mainly been depending on what is my camber angle, and what is my say… s by c ratio. It says, this m parameter, that is very important. This is nothing but it is airfoil parameter. Just look at, this is what is my airfoil. If I am looking at, this is what is the location where I will be having my thickness to be maximum. This is what is representing say maximum camber location, I say…that point as a point 'a'; so this is what is say my point 'a', okay. And, this is what is in reference to chord. So, here we have written that as 'l', because I am using this nomenclature. Basically, this is nothing but this is what is my chord, okay.

So, what it says? My $m = 0.23\left(\frac{2a}{c}\right)^2 + 0.1\left(\frac{\alpha_2}{50}\right)$. Suppose say, if I am considering this equation for say rotor blade, in place of α_2 we will be having β_2, okay. And as we have discussed, 'a' is a distance of the point of maximum camber; so, this is what is a location of maximum camber from the leading edge, okay. This 'm', that's what is varying with different kinds of camber lines what we are selecting. We will see what exactly is a meaning of different kinds of airfoil, very soon.

It says when we are having say circular arc camber line, my $\frac{2a}{c} = 1$; and we know like deviation angle, it is inherent property for say our airfoil. So, same logic that can be applicable for our inlet guide vane also. So, what it says for inlet guide vanes? This deviation angle, that's what is given by $\delta = 0.19\,\theta\left(\frac{s}{c}\right)$, okay. So, this is what will give us idea about how our deviation angle that's what is changing with. Now, as we have discussed, we are moving towards very aggressive designs.

When I say very aggressive design, the meaning is we are moving towards say high pressure rise to be expected from our blades. When we say we are expecting high pressure rise, it is prone to happen my $\Delta\beta$; that's what is going to be high, okay. And under that condition, we need to do careful calculation for this deviation angle. So, based on older available data from the cascade tunnel, people they are taking this deviation angle as a first cut approximation. Now, with availability of our computational tools, people they are realizing what is happening near the trailing edge.

And based on the flow visualization, based on C_p distribution, based on detailed flow field study; people they are modifying this deviation angle. And just try to make the flow to be in line to what we are expecting, okay. So, the use of this computational tool, that's what is helping us in sense of deciding this deviation angle. Now, what we are talking about this deviation angle calculation using say computational tool that's what is depending on what kind of say turbulence model we are selecting with, okay. We will be discussing what all are the effect of change of Reynolds number; because that's what is very important in sense of calculation of this deviation angle.

So, we can say, today we have discussed about how do we move with the change of say incidence angle. What all are the parameters which affect the incidence angle, and we have realized my mass flow rate, speed, Mach number, Reynolds number; they are the flow parameter we are changing the incidence angle. At the same time, we are having our blade geometry, we are having our thickness distribution, the shape of leading edge, shape of the trailing edge, the radius of the leading edge; all those say blade parameter or the cascade parameters, or we say airfoil parameter, that's what is changing the incidence angle.

And we have started discussing about with the change of incidence angle; at the exit we will be having the change in the deviation angle. And, we learn, deviation angle that's what is prone to happen because of the inherent property of our airfoil. And we need to be very careful in sense of calculating this deviation angle, okay. So, with this we are stopping with; see you in the next lecture. Thank you, thank you very much!