Aerodynamic Design of Axial Flow Compressors & Fans
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Lecture – 25
Cascade Aerodynamics (Contd.)

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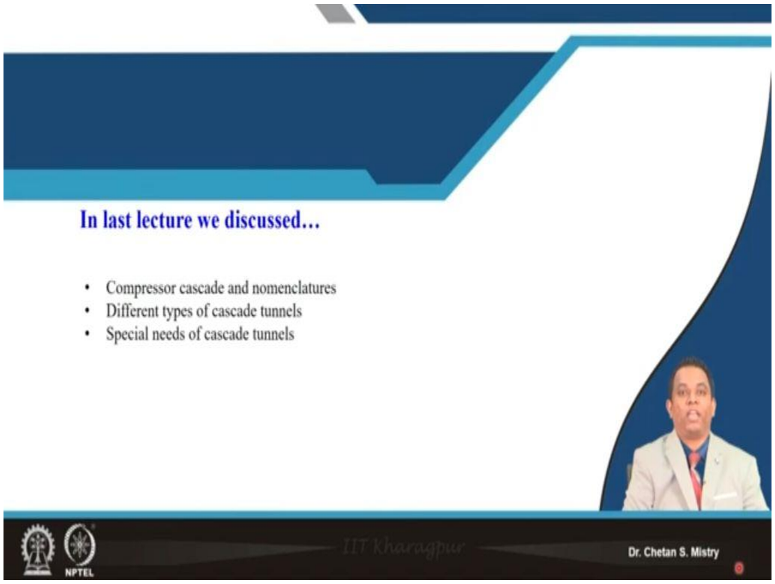

In last lecture we discussed…

- Compressor cascade and nomenclatures
- Different types of cascade tunnels
- Special needs of cascade tunnels

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Hello, and welcome to lecture 25th. So, in last lecture, we started discussing about compressor cascade and various nomenclatures. And we realize what we have learned from our fundamental; that's what we were discussing about the air angles. We are more interested towards say reality, means we have introduced other angles. Like we have introduced the angles, they are known as say… incidence angle, deviation angle, camber angle, stagger angle. And what we realized, say…our blades they are being made for particular angles, which we have already been calculated with.

And because of my in-flow condition, it may possible that, that (flow) will not be incident at a design angle. And that will be entering or that will be striking on blade leading edge at other angle, and that's what we have defined as say incidence angle. In line to that we have realized because of presence of low momentum fluid, and because of our viscous effect under adverse pressure gradient, we are having the effect that's what is giving my flow exit angle to be deviate from the design; and that's what we have defined as say deviation angle. Then, we have discussed about the camber angle, that's what we have defined as a tangent drawn from leading edge to camber line, and tangent drawn from the trailing edge to the camber line, that’s what is making the angle we have defined as a camber angle.

And later on, with axial direction what my blade that’s what is making angle; that’s what we have defined as a stagger angle. Now, in order to go into detail, we need to realize how do we measure or how do we use these airfoils for our further design process; we have introduced different types of cascade tunnels. So, we have discussed about linear cascade tunnel, we have discussed about say annular cascade tunnel, we have discussed about sector annular cascade tunnel. There we have realized these all tunnels; they are having their own importance.

If we consider linear cascade tunnel, in which at particular station what airfoil we are having, that’s what will be coming into the consideration for the study. So basically, that’s what is giving blade-to-blade information. Same way, near endwall region that’s what is giving idea about the formation of secondary flows. But, the limitation we have discussed, that it is not possible to consider the variation of pressure along the span. Because, we are neglecting or say this is not taking care of your radial equilibrium.

But, at the same time, it has its own benefit. Like we have discussed, my flow that’s what is happening on the blade or airfoil that what is initially laminar flow. In between, at say about 30 to 40 percent of my chord, my flow will be of say transition nature; and later on, downstream of my trailing edge or towards my trailing edge, my flow that’s what is turbulent. So, what is happening on that blade surface that’s what is of our interest. Same way, how my pressure it has been distributed on pressure surface and suction surface; that’s what is giving me what is my lifting coefficient or C_L.

And that lift coefficient we have correlated in sense of pressure rising capacity of that particular airfoil. Now, the flow behavior, that’s what is changing as we have discussed with the change of incidence angle; so that’s what is possible for measurement; or we can realize what is happening in sense of change of C_p. Suppose, if I consider different geometrical parameters that also can be studied by using this linear cascade tunnel. Then, in order to have understanding of three-dimensionality, we are having the options with say annular cascade tunnel. But, the problem is say, if we consider particular stage of my compressor, it maybe having more number of blades.

So, in order to do that simulation, I need to have more number of blades to be made. Secondly, in order to test that at the particular boundary condition, my power requirement will be very huge. The size of the tunnel also will be very huge; and that’s what is putting constraint in sense of use. But, still people in order to realize the real actual working condition of the engine and the components, they are using as on today also.

Now, the trend that has come, it is to use sector annular cascade tunnel; that’s what is limiting or that’s what is giving the benefit in sense of having, we are having number of blades required to be considered for study will be lower. At the same time, we can change… we can scale our blade as per the requirements; so that’s what is giving so much of flexibility in sense of understanding what is happening on my blade surfaces.

At the same time, the same three-dimensional blade what we are using for our engines, that can be tested there. So, that’s what all we were discussing in sense of our cascade tunnels and their use. Now, let us try to understand like what all angles we are discussing, how do we realize that for use for our design purpose.

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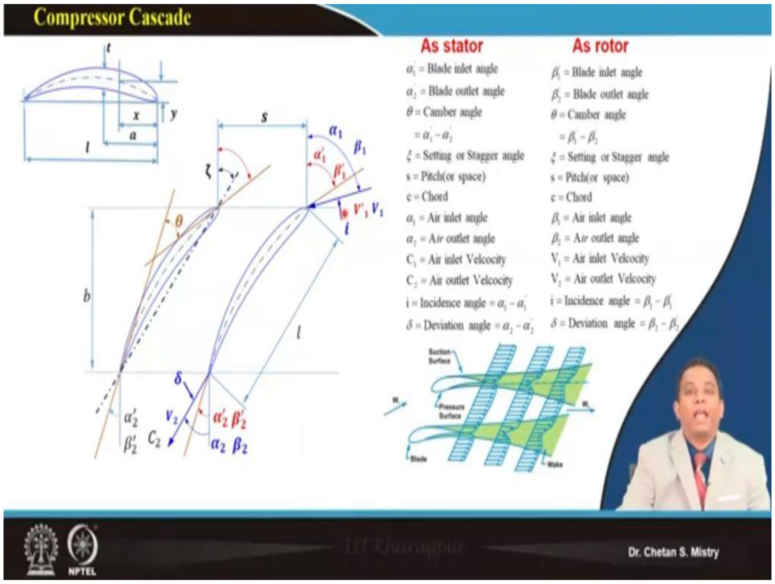

Compressor Cascade

As stator	As rotor
α_1' = Blade inlet angle	β_1' = Blade inlet angle
α_2' = Blade outlet angle	β_2' = Blade outlet angle
θ = Camber angle	θ = Camber angle
$= \alpha_1' - \alpha_2'$	$= \beta_1' - \beta_2'$
ξ = Setting or Stagger angle	ξ = Setting or Stagger angle
s = Pitch(or space)	s = Pitch(or space)
c = Chord	c = Chord
α_1 = Air inlet angle	β_1 = Air inlet angle
α_2 = Air outlet angle	β_2 = Air outlet angle
C_1 = Air inlet Velcocity	V_1 = Air inlet Velcocity
C_2 = Air outlet Velcocity	V_2 = Air outlet Velcocity
i = Incidence angle $= \alpha_1 - \alpha_1'$	i = Incidence angle $= \beta_1 - \beta_1'$
δ = Deviation angle $= \alpha_2 - \alpha_2'$	δ = Deviation angle $= \beta_2 - \beta_2'$

So, let us take our first; this is what we have discussed in sense of incidence angle, so let us see. This is what we have defined as an incidence angle. So, at the leading edge, my flow that’s what will be the incident at a particular angle, okay, and that’s what is other than the design angle; that’s what we have defined as an incidence angle, okay.

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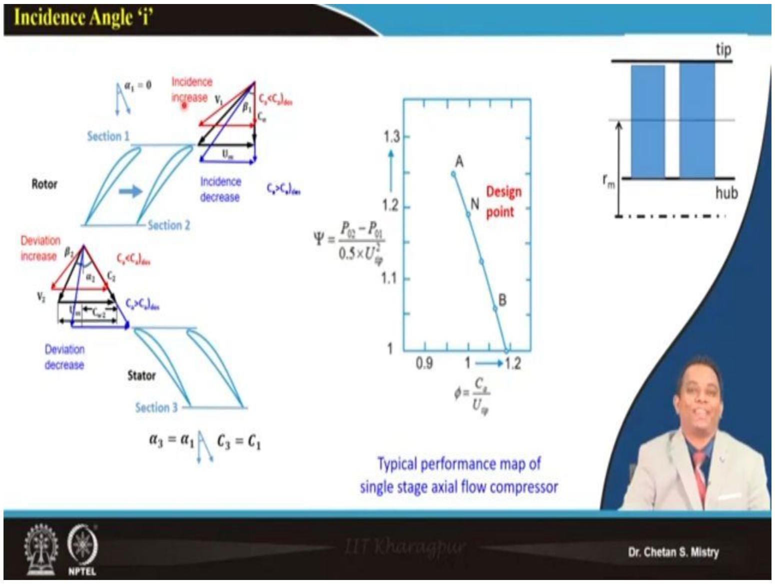
Incidence Angle 'i'

Typical performance map of single stage axial flow compressor

Now, let us try to look at how exactly we need to realize for our actual working condition. So, here if you look at, this is what is representing the performance map for single stage compressor. So, on X-axis, we are having C_a/U_{tip}; sometimes people they are using C_a/U_{mean}, also. So, C_a is nothing but that's what is my axial velocity. And U_{tip} that's what is say my peripheral speed at the tip, and that's what has been represented in sense of maybe pressure ratio, or pressure rise coefficient. So, pressure rise coefficient, we are defining as

$$\Psi = \frac{(P_{02} - P_{01})}{0.5 \times U_{tip}^2}$$

Now, here somewhere, this point, that's what is say point N; we can say that as a design point. So, for all components, say… mainly suppose if we consider for the compressor, that compressor we are designing for one particular design condition. That's what we can say design speed is 100 percent speed, that's what is say for particular mass flow rate and my expected pressure rise. So, we can say, this is what is my design point or design condition. Now, if we look at, suppose if we are having this compressor, which is having say axial entry; so we can say, this is what will be my velocity triangle.

So, this is what already we have discussed in sense of my axial velocity, peripheral speed, relative velocity; this is say my air angle, we can say it is β_1, okay. Same way at the exit, we can say my flow that will be coming out with some air angle β_2 with velocity V_2; if we are having our peripheral speed, we can put it here. That's what will be giving me my absolute velocity and my angle α_2. And we have our whirl component that's what we have defined as C_{w2}. And if we consider our design for the stage is such that my entry and exit that's what is axial, we can write down my C_3 and C_1 that's what is same; my α_1 and α_3, that's what is same.

Now, let us try to move for this case. Suppose say for the same case, I am moving towards say point A. Let us try to understand, say point N and we are going towards point A. When I say I am moving towards point A, we can say I am decreasing my mass flow rate; or we can say if my peripheral speed it is same. Suppose, if I consider it is rotating at the same speed, the movement from point N to A is nothing but that's what is representing decrease of my axial velocity. So, if we are putting this, that's what is say, this is what is say less than that of my design axial velocity.

So, if I will be putting this, this is what will be my axial velocity. Since my peripheral speed we have considered to be same; and if I will be joining, that's what is representing this is what is my velocity triangle. So, just try to understand what we have done. We have moved from point N to point A, where my axial velocity is lower. Suppose, if I consider I am having second configuration, that's what is say, if I will be moving towards point B, that point B is nothing but that's what is representing higher value of my axial velocity or higher mass flow rate.

So, if I will be putting that; in that sense, this is what will be the change of my velocity triangle. Just understand, remember these things, this is what is very important. Here in this case, we know the characteristic of our compressor is with decrease of my mass flow rate, my pressure that will be rising. Now, this is what we have represented in sense of my velocity triangle. So, if I will be writing here, I have my change of angle from β_1 to some β_1'. If I am considering, I am having say decrease of axial velocity; that's what I am saying, this is what is increase of my incidence angle, okay.

Now, same way, here this is what I am writing as say incidence, it is decreasing or decrease of incidence. So, let us say like we are now discussing rather changing of angle from β_1 to β_1' and β_1'', we are writing that in sense of change of incidence. We can say, when I am having my axial velocity that's what is decreasing, I have my incidence angle that's what is increasing. When my axial velocity is higher, my incidence angle, that's what is decreasing. In line to that, suppose, if we consider say at the exit condition; so same way because of change of my axial velocity, this is what I will say will be my velocity triangle.

Now, look at here, if we look carefully, this is what is representing the change of incidence to my blade. Now, because of change of my incidence, I will be having the change of outlet angle. And we know at outlet we are defining that in sense of outlet angle, say β_2; or in other language we are defining that as a change of angle, we are defining that as say deviation angle. So, suppose this is what is a case for my lower axial velocity, in line to that I will be putting this for my say higher axial velocity. So, this is what is representing the increase of deviation angle because of say decrease of axial velocity; and this is what is representing the decrease of deviation angle.

So, now here you can understand, like when I say with the performance map, what is happening? So, you know, this is what is my design condition. Now, let us discuss about the engine, what is happening? Most of the time my engine, that's what is working under off-design condition. When I say off-design condition, means during my takeoff I am looking for maximum amount of thrust, that's what where my engine that will be rotating or say running at 100 percent speed. Now, as per my thrust requirement, you can understand, I need to have higher pressure rise; and that's what is giving me my movement from point N to say A.

In line to that when it is flying at the cruise condition, it maybe possible that it will be required like pressure rise to be lower. And that lower pressure rise we can say roughly at this moment as say point B. You know, like the change of my requirement of thrust, that's what has been managed by different ways. One of the way is by managing the mass flow rate through the engine; and second, that's what is by changing the speed or rotational speed of the wheel, or rotational speed of my compressor. So, here this is what is representing what is happening at the constant speed configuration.

So, we can say when we are having our constant speed configuration and when we are having decrease and increase of mass flow rate, we are having change of incidence angle and we are having change of deviation angle. Now, let us see what we were discussing.

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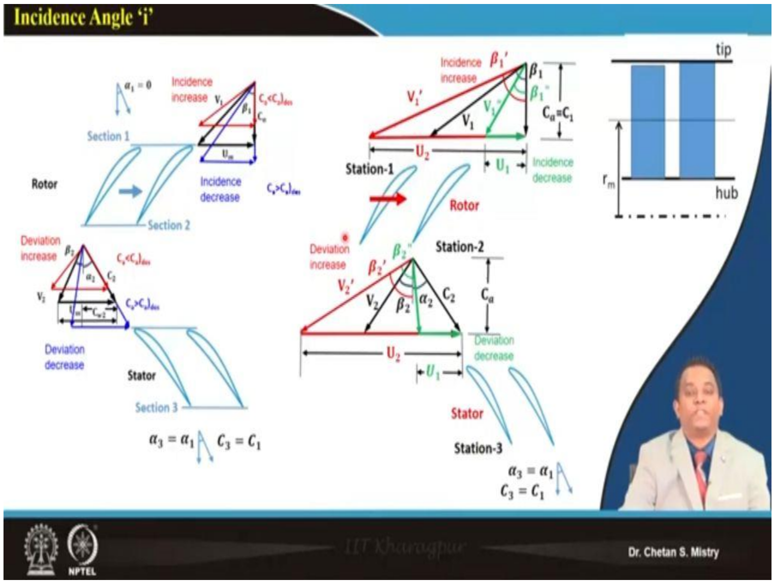

Suppose, if I consider, this is what is representing the different condition. As we discussed, maybe… I may be running my engine at the high speed; so you can say, this is what is representing this red color one, that's what is representing when I am running my engine at the high speed. And this green color one, that's what is representing when I am running my engine at the low speed. So, in line to what we have understood, here if you look at, my mass flow rate that's what is constant. So, if this is what is my configuration, we can say, still here in this case we are having say increase of my incidence angle, when I say, I am increasing my peripheral speed.

Same way here, this is what we can say my incidence angle, that's what is decreasing. Now, if you look at the exit condition, we will be having similar kind of trend; because my peripheral speed, that's what is coming to be higher. That's what will be giving me my deviation to be increased when my peripheral speed is increasing; and here in this case, my deviation, that's what is decreasing with the decrease of speed. So, you can understand, my blade all the time, that's what is working under different flow incidence. It is working at the design incidence condition, it maybe working at say increased incidence angle, it maybe working at the decreased incidence angle.

And because of change of my incidence angle at the entry of my blade, now if you look at, at the exit also my flow field, that's what is changing; and that's what is very important. So, let us try to understand what all are the impacts of change on this incidence angle.

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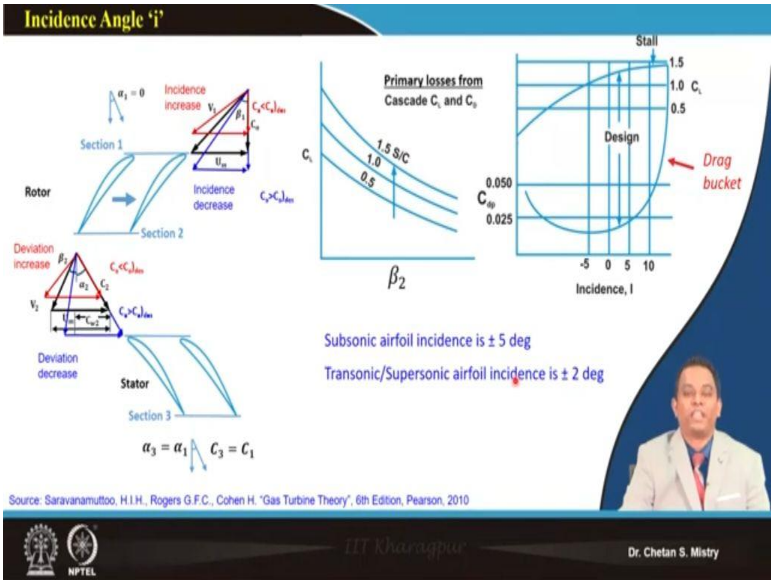

Incidence Angle 'i'

Subsonic airfoil incidence is ± 5 deg

Transonic/Supersonic airfoil incidence is ± 2 deg

Source: Saravanamuttoo, H.I.H., Rogers G.F.C., Cohen H. "Gas Turbine Theory", 6th Edition, Pearson, 2010

Now, we have our fundamentals that's what is available with us. What we can see here, this is what is representing, say change of incidence angle with the change of my C_D, drag coefficient, and this is what is representing my lift coefficient (C_L). So, this is what is my characteristics of airfoils. Now, here if you look at, suppose somewhere here, I am having some design point; so that's what already I have designed with. Now, what happens? If I say my incidence, that's what is increasing; so I say, this is what is the increase of incidence say $+5, +10$, we can look at that's what is giving me higher C_L. So, when I say it is giving higher C_L, the meaning is my lift coefficient is rising.

Now, when we are talking about the airfoil for particular blade for axial flow compressor, we can say it is increasing my pressure rising capacity. So, with increase of my incidence angle, we are having the increase of pressure rising capacity, but there is a limit, okay. Here if you look at, somewhere it is written is a stall. So, if you move beyond that point for particular incidence angle, we will be having stall of airfoil; and that's what will lead to increase my drag, okay. And here if you look at, this is what is representing with increase of my incidence angle, we are having our drag to be increased; that's what we say, we used to say that as a drag bucket, okay.

Now, let us look at on the other side when we are having say negative incidence angle; you can see, my lift still it has been generated, but it is lower compared to what lift we are expecting. So, the meaning is, this is what is giving us idea like my pressure rising capacity of particular airfoil that's what is decreasing, okay. So, this is what we need to remember, this is what is very important. And as I told, as aero-dynamist many people, they used to say, this as say angle of attack; but for our conventional language, we are writing that as say 'incidence angle'. Now, this is what is representing how my solidity that's what is changing with, say you know, with variation of β; and this is what is giving me my lift coefficient.

So, you can understand, if I will be increasing my solidity, that's what is giving me; say it is a inverse of solidity; that's what we can say, it is giving high lifting coefficient. Now, the question will come, say… what need to be the incidence? Or like, how do we decide with the incidence and what to do with the incidence, because that's what is very important, okay. So, what it says… when we are having, say… our airfoils, which are subsonic airfoils, my incidence that can be varied from $+5\ to - 5°$; when we are having transonic or supersonic airfoils, my incidence that's what is $\pm 2°$.

Here, we need to realize one thing, as we have discussed for airfoils or kinds of airfoil what we are using for say subsonic application, kind of airfoil we are using for transonic application; they all have different leading edge thickness. So, if we consider for subsonic airfoils, my leading edge thickness, that's what is slightly higher on side. So, if we look at for NACA 65, or when we are looking for C4 kind of airfoil, their leading edge are thicker leading edge. And that's what is a little insensitive with the change of incidence angle. And that is the reason why this is what is giving us flexibility of variation, or that can tolerate $\pm 5°$.

Now, when we are talking about the transonic airfoils, my leading edge radius, that's what is smaller, and that's what is very sensitive. We intentionally are looking for leading edge radius to smaller because we want to have attachment of our shock with the blade. And that is the reason why the leading edge radius, that's what is smaller. So, that is the reason why it is very sensitive with the change of incidence angle. Now, here in this case, let us see what all will be the changes; here this is what is representing in sense of C_D and C_L.

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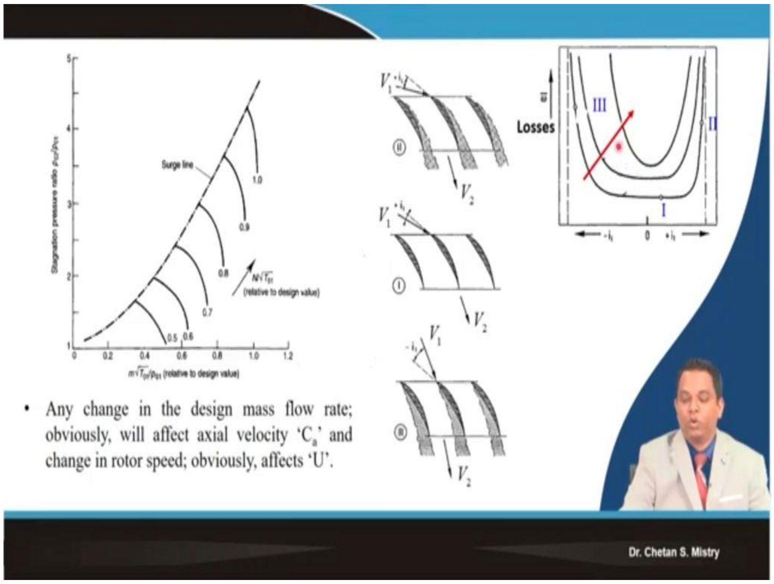

- Any change in the design mass flow rate; obviously, will affect axial velocity ‘C_a’ and change in rotor speed; obviously, affects ‘U’.

Now, what is our interest? So, here if you look at, this is what is representing my performance map for axial flow compressor. Here if you look at, this is what is representing my non-dimensional speed; we can say… say 70 percent, 80 percent, 100 percent, this is what is particularly representing my surge line. And in line, we are having say mass flow rate that’s what is in sense of non-dimensional form; and this is what is representing my pressure ratio. Now, when we are talking about the change of my speed, or the change of my axial velocity, this is what is the meaning.

So, if you look at a different speed configuration, my stall mass flow rate, that’s what is different. At the same time for different speed combination and mass flow rate combination, my pressure rising capacity, that’s what is different. So, it is very important for us to realize what is happening with the change of my mass flow rate and what is happening with the change of our peripheral speed. Here in this case, this is what is representing three different conditions, because we are more interested in sense of total pressure.

So, here if you look at, this is what is in line to what we have discussed. So, here we can say, we are having positive incidence angle, negative incidence angle; and this is what is representing the losses; these losses are nothing but the total pressure losses, okay. Now, here if we try to look at, this is what is my condition-1; so, we can say this is what is my design condition. Now, look at here, this is what it say I am having my design condition. So, suppose say…if I say, I have designed for some positive incidence angle, my flow will behaving absolutely fine; and that’s what will lead to give you the losses to be lower, okay.

Now, what is happening? Suppose if I consider, I am increasing my incidence angle, so realize the thing when I say I am increasing my incidence angle; that means I am changing my axial velocity, or I am changing my peripheral speed. So, you can say I am decreasing my mass flow rate or axial velocity, or I am increasing my peripheral speed. Under that condition, there is a possibility that your flow will get separated from the suction surface. And when we say there is a separation of my flow from the suction surface; that’s what we have defined as a stall. And because of that, if you look at this is my condition-2. What it says?

I am going to increase or I will be having my losses to be increased; rather increase of losses, my performance is more important. We have discussed, we need to have our engine to operate near to this surge line, not exactly very near to surge line or on surge line. If this is what is crossing to the surge line, the engine will go fail, okay; and that is the reason why these losses that’s what is always very important, okay. Now, look at the different conditions. Suppose, if I consider, say we are having our incidence angle; that’s what is say lower; so, this is what is representing negative incidence angle.

Under that condition, there maybe chances that my flow will get separated from the pressure surface. So, for negative incidence, for that also we have extreme. It says when I am moving more towards the negative incidence angle, we will be having more losses that’s what is happening. And those losses are because of your say change of incidence angle, and because of the flow separation that’s what is happening on my pressure surface. Now, this is what is representing when I say I am changing my condition say my operating condition, say mass flow rate when I am changing my peripheral speed.

So, you know, like with the change of other than the design condition, blades will become very sensitive, okay. So, if here if you look at, this is what we can say, it is my safe operating range; but when I am moving towards the other condition, we are having our operating range, that’s what is increasing. So, that’s what is decreasing in that particular sense, okay. So, this is what is very important for us to understand what is the meaning of change of incidence angle?

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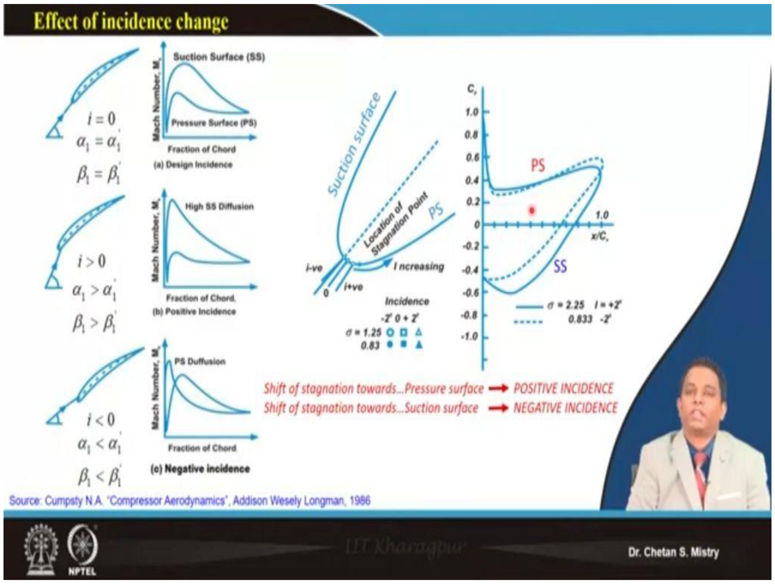

Effect of incidence change

Shift of stagnation towards...Pressure surface → POSITIVE INCIDENCE

Shift of stagnation towards...Suction surface → NEGATIVE INCIDENCE

Source: Cumpsty N.A. "Compressor Aerodynamics", Addison Wesely Longman, 1986

Now, let us try to understand that with say change of Mach number on the surface. So here, if you look at, we are having three different conditions. We have our incidence angle to be 0, what is the meaning of that? You can say my α_1 if I am talking about the stator, then my blade angle and air angle they both are same. Similarly, we can say if it is for rotor, we can write down $\beta_1 = \beta_1'$. So, this is what is representing my incidence angle to be zero condition. Now as we have discussed, we can have our incidence angle that's what is greater than 0, okay.

So, the meaning is here we can say my α_1 that's what is greater, my β_1 that's what is greater, okay. And we can have third condition in which my incidence angle that's what is say less than 0; so, this is my configuration. Now let us try to look at what is happening on the suction surface and the pressures surface of our blade. So, here in this case, this is what is representing the Mach number distribution on the suction surface, and Mach number distribution on say my pressure surface. Sometimes people they are using Mach number also for the study. Mainly, if we are considering the static pressure or the surface static pressure, that's what is giving more detail understanding.

But, here for the sake of understanding, let us take this as a Mach number configuration. So, here if you look at, what we have learnt from our fundamentals that, you know, at the initial stage of my blade, say near my leading edge, I will be having the flow acceleration that's what is happening up to say 10 to 20 percent of my chord. So, we will be having a whole lot of acceleration that's what is happening on the suction surface. And or later part, if you consider, this is what is we can say it is a diffusing passage; my passage area is diffusing, my flow will get decelerated.

So, this is what is representing the deceleration process, we can say the decrease of Mach number. So, this is what is happening on my suction surface. In line to that if we consider say…on my pressure surface, again at pressure surface, we will be having some acceleration at the initial stage that’s what is happening; and we will be having some deceleration of the flow, maybe on the later part of my blade, we will be having constant Mach number kind of configuration. And as we have discussed, this is what is representing my pressure rising capacity of the blade, okay. So, this is what is say my design condition, I say my incidence angle, that’s what is say zero.

Suppose, if I consider, say…we are having our incidence angle to be say… greater than 0, so what will happen? You know, my streamline or my stagnation point, that’s what is moving towards the pressure surface. Just look at, this is what is the meaning of positive incidence angle, or we can say my incidence angle that’s what is greater than 0. So, we can say here, my flow will incident on say towards my pressure surface. If this is what is your case, you can say we are having a whole lot of acceleration, or great acceleration that’s what will be happening on the suction surface up to 10 to 15 percent of chord.

So, here we are having great acceleration that’s what is happening; and on later part, we will be having the diffusion that’s what is happening, okay. So, it says high suction surface diffusion, that’s what is happening on my suction surface. Now, here if you look at, what is happening on my pressure surface? So, if you look at on my pressure surface, we are having the acceleration that’s what is happening. But, it is comparatively less when we are comparing zero incidence case in this case. So, here in this case we are having small acceleration, that’s what is happening on my pressure surface; and we will be having nearly constant Mach number or constant pressure rise on my pressure surface. Now, if you compare these two curves, particularly, that’s what is representing when we are having our incidence angle to be greater than 0, or pressure rising capacity that’s what is increasing.

So, if you recall, we have discussed about say performance map for single stage compressor, where we have discussed when we are having our axial velocity, that’s what is decreasing. That’s what is giving the rise of pressure and we have discussed that as a positive incidence case; so, this is what is positive incidence case. Now, if we move, suppose if I consider my incidence angle is less than 0, we can say, we are having say negative incidence angle; then my stagnation point, that's what will not be at exactly center, but it will be moving towards the suction surface. So, you can say this is what is a place where my flow is getting incident, okay.

So, this place we are having the flow incidence that's what is happening. If that's what is your case, you know, we will be having our flow acceleration, that's what is happening on my suction surface; at the same time, great acceleration that's what is happening on my pressure surface. And here if you look at, we will be having the distribution of my pressure or Mach number that's what is coming to be different. And that's what is indicating, there is a deterioration in sense of performance or the pressure rising capacity of my blade, okay. Now, this is what we need to realize; we can say, this is what is my pressure surface, and this is what is say my suction surface.

And now onwards, we need to remember the thing when we are having shifting of our stagnation point towards the pressure surface; that's what we are defining as a positive incidence angle. When my stagnation point, that's what is moving towards the suction surface, we can say that as say…negative incidence angle. So, this is what is universally accepted nomenclature; people they are defining the change of incidence angle with reference to movement of stagnation point. Maybe it is moving on pressure surface or maybe it is moving on the suction surface. And let me show you here, this is what is representing the C_p distribution, particularly when we are having say positive incidence angle and negative incidence angle.

And we can realize, what we are discussing in sense of positive incidence angle, we are having the management of…proper management of flow; that's what is happening on my pressure surface as well as on my suction surface. And do not forget all the time, it is mean the major contribution for pressure rising capacity of any kind of airfoil what we are using for axial flow compressor, that's what is mainly been depend on what is a surface curvature for the suction surface, okay. So here, when we are having say negative incidence, we can say, we are having say deterioration in sense of performance. So, let us see what all we have discussed today. So, we have started discussing about the incidence angle, and we have realized.