Aerodynamic Design of Axial Flow Compressor & Fans
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Lecture 36
Design Strategies (Contd.)

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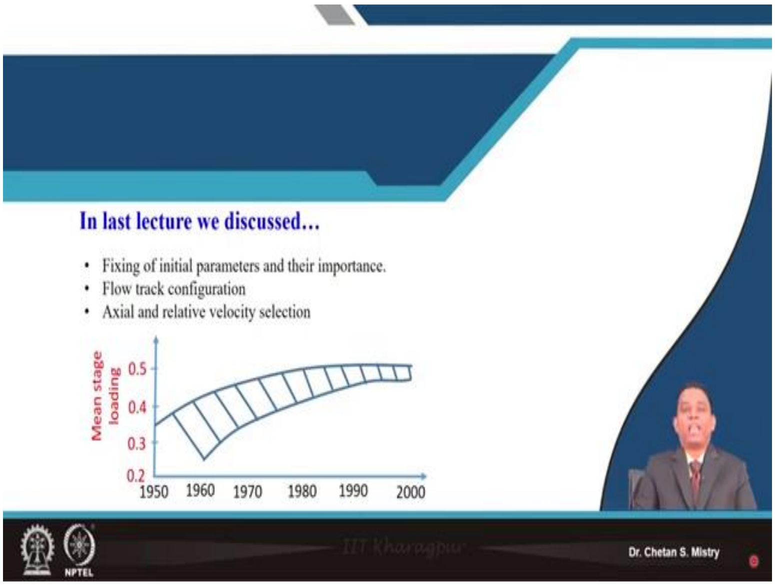

Hello, and welcome to lecture 36, we are discussing about design strategies. So, in last lecture we were discussing about the fixing of initial parameters and their importance. So, initially we have introduced two parameters, that's what is my flow coefficient and loading coefficient; later on we have started discussing about what will be the effect of different parameters on say stage efficiency. So, we have combined the parameters called say degree of reaction, diffusion factor, loading coefficient and my flow coefficient; and their impact on say stage efficiency.

Now, day by day, as we have understood, our expected total pressure ratio or say pressure rise from say from the engine that's what is increasing and that's what lead to increase say per stage pressure ratio. Now, when we say per stage pressure rise we are expecting to be larger that says my mean stage loading factor that's what will be increasing and that's what is putting so many constraints in sense of our aerodynamics as well as in sense of my operation, okay.

Because efficiency, that's what is one concern, overall operating range that's what is second concern and, you know, stall limit or say surge limit, that's what is coming also as one of the limit. Now, we have introduced one more parameter, that's what is called say axial velocity density ratio and that also people they are selecting for say initial stage of calculation.

Then we were discussing about what is the effect of relative velocity and we have realized when we are having our relative velocity at the outlet to be lower it says, it represents say effective diffusion. There are cases where we are having say exit and inlet relative velocity to be same, when we say, we are having our degree of reaction to be 0. And there are special designs where intentionally we are looking for exit relative velocity to be large. Let us move to the next step.

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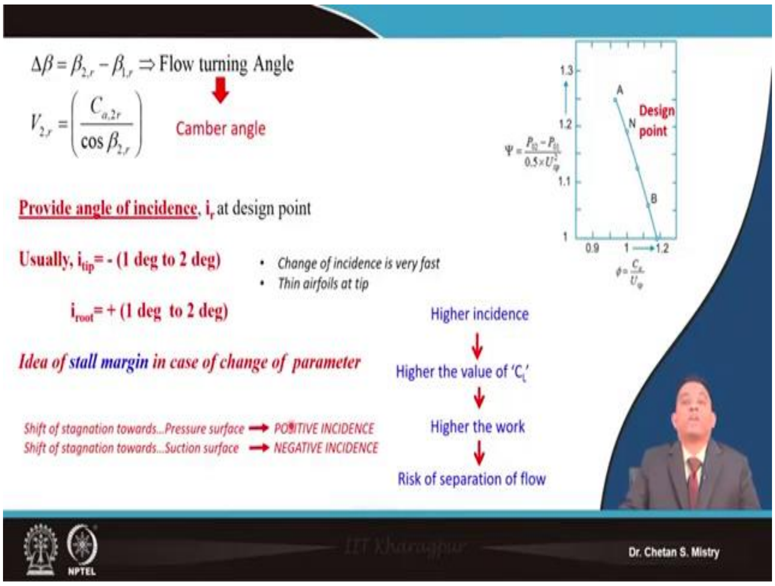

Now, once we have done all these parameters in sense of calculation, later stage that's what will be coming is we are looking for $\Delta\beta$, that $\Delta\beta$ is nothing but my blade turning angle. Now, if you recall, when we are saying my flow that's what is entering at some angle, blade angle, say β_1 or say air angle β_1.

Then we started discussing about the introduction of parameter called incidence angle. Now, what we have realized, when we are increasing our incidence angle, we are increasing our lift coefficient, that's what is the characteristic of our airfoil. When we are increasing our lift coefficient, that's what is increasing our pressurizing capacity when we are saying this airfoil it has been used for say axial flow compressor or maybe for fan, okay.

Now, what happens when we are increasing this say C_p distribution, it says per stage pressurize we are getting to be higher, but at the same time, beyond certain number there may be possibility that your flow will get separated from the blade. At the same time, we were discussing about say negative incidence angle where we are having say our pressurizing capacity or my C_p distribution that's what was coming to be lower.

Then we have realized, suppose if we consider, this is what is our performance map and say end point that's what is say my design point, we can say, this is what is my design mass flow rate and my design pressure ratio. Now, when we are decreasing our mass flow rate, my pressure that's what is going to increase and my point that will be shifted from say point N to point A, and beyond that point we will be having say stall that's what it says like stall point.

Now, what is happening? We learnt for constant, say, rotational speed, if we are reducing our axial velocity that's what will lead to increase my incidence angle, okay. Now, this incidence angle when it is increasing, we realized that's what is increasing my C_L and that is the reason why we are getting high pressure rise. Remember, that's what we are discussing about single airfoil, my blade is made up of number of airfoils. So, all together, that's what will be giving me rise…pressure rise.

If he considers, say, second point, suppose I am moving towards say on high mass flow rate side our incidence, that's what is going to decrease and that's what will lead to reduce my C_L and that's what will lead to reduce my pressure rising capacity. So, we can say, our pressure rise expected, that's what will be lower. So, we have now variation of incidence angle in positive and negative sense.

What we have introduced? We say, like, this need to be in particular range, okay. Suppose, say if you are considering near the tip region, we need to introduce our incidence angle that's what will be in the range of negative say 1 to 2°, near the hub we need to introduce say our incidence angle to be positive.

Now, realize one thing, this is what is not we are calculating, this is what we are putting in the design point, okay. So, purposefully we are introducing this incidence angle at the initial stage of design, so that when it is working under of design condition it will still behave like working in a design condition.

So, here if you look at, here we can say, my incidence that's what is say going to reduce. So, you know, this incidence what we are putting near the tip it is negative that's what will be taking care of that situation, okay. And we have realized, do not forget, when we say our incidents to be negative and when we say our incidence to be positive, that's what is based on where my stagnation point that's what is located at the leading edge.

We realized, when we say, my flow that's what is incident on the pressure side, that's what we are defining as a positive incidence and when we are saying our flow that's what is incident on say suction side, that's what we have defined as a negative incidence, okay.

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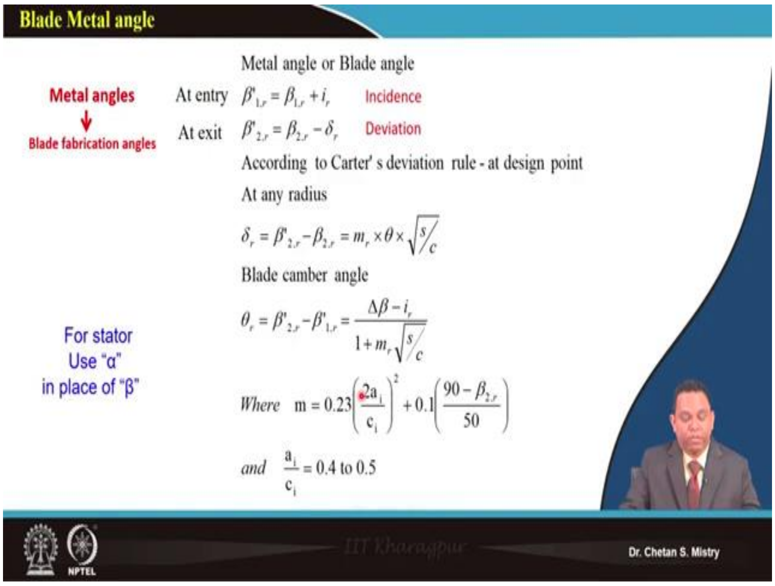

Now, let us see, like, how we will be using this for our design purpose, okay. So, you can say, now as we have discussed earlier also, say, now I am putting what angle we are writing, that angle we are writing as say blade metal angle or blade fabrication angle, that's what is given by say this is what is my case, it says my $\beta_1 \pm i$, that's what is at my entry, okay.

Same way, at the exit, we have introduced the angle that's what is called deviation angle and when we are making our blade that deviation angle, that's what we are reducing or say that's what is say minus. So, this is what is say my outlet angle, that's what is minus this deviation angle. So, remember now this dash, that's what is representing my metal angles.

$$Metal\ angle\ or\ Blade\ angle$$

$$At\ entry, \qquad \beta'_{1,r} = \beta_{1,r} + i_r\ (Incidence)$$

$$At\ exit, \qquad \beta'_{2,r} = \beta_{2,r} - \delta_r\ (Deviation)$$

So, at the entry, suppose say I am having negative incidence, this will be $\beta - (-i)$, if it is positive, it will be positive; and my deviation angle always we are subtracting from our metal angle from our flow angle, okay. Now, if this is what is your case, in order to calculate our deviation angle, we are using our Carter rule, okay.

So, as per the Carter we can write down, this deviation angle at any radial station, that's what is given by $m \times \theta \times \sqrt{s/c}$, okay. Now, this camber angle, so theta, that is nothing but it is a say camber angle that camber angle we can calculate based on my $(\Delta\beta - i_r)/(1 + m_r\sqrt{s/c})$, okay.

$$According\ to\ Carter's deviation\ rule - at\ design\ point,$$

$$At\ any\ radius$$

$$\delta_r = \beta'_{2,r} - \beta_{2,r} = m \times \theta \times \sqrt{s/c}$$

$$Blade\ Camber\ Angle,$$

$$\theta_r = \beta'_{2,r} - \beta'_{1,r} = \frac{\Delta\beta - i_r}{1 + m_r\sqrt{\frac{s}{c}}}$$

$$Where, m = 0.23\left(\frac{2a_i}{c_i}\right)^2 + 0.1\left(\frac{90 - \beta_{2,r}}{50}\right)$$

$$and\,\frac{a_i}{c_i} = 0.4\ to\ 0.5$$

Now, if you are putting this 'm', this is what is called 'm' parameter, it is given based on say a/c. So, a/c, is nothing but that's what is representing where I will be having my maximum camber.

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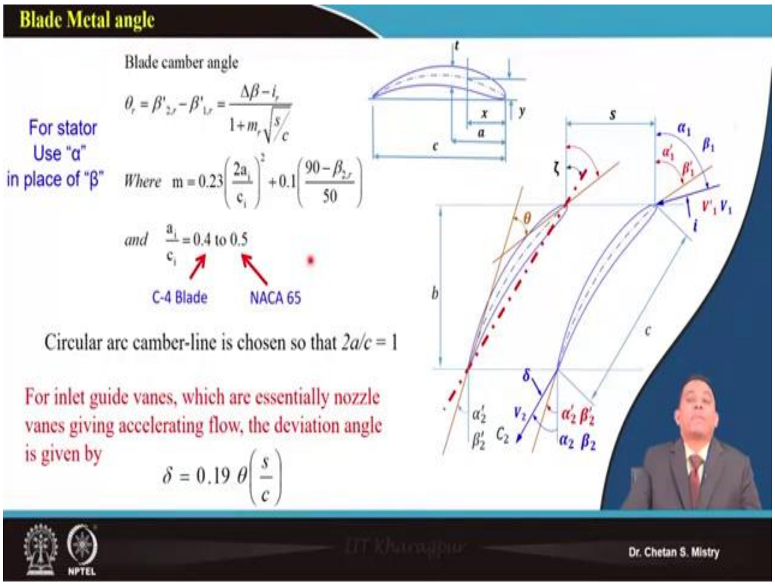

So, let us see what is this case? It says, here, this is what is say 0.4 when we are talking about our airfoil to be C4 airfoil and it is 0.5 when we are using our NACA 65 airfoil. Now, the question must arise, here we are writing in sense of β, suppose we are doing our calculation for the stator, we need to replace this angle by α, okay. So, for stator also, we will be having incidence angle, for stator also we will be having deviation angle. And this is what we need to calculate for both stator as well as for the rotor.

It says for circular camber line, this $2a/c$ that's what we are taking as 1 (one), and for inlet guide vanes, which is we are using for say accelerating our flow, this deviation angle that's what is given in sense of my camber angle and in sense of my s/c, okay. So, do not forget what all we have discussed up till now in sense of our cascade aerodynamics.

So, these angles…these angles are of importance when we are making, we are fabricating our blades, okay. So, just realize the thing, this incidence angle, purposefully we are assuming this incidence angle. It says when we are using say our subsonic airfoils, safely we can assume say $-5°$ at the tip region and $+5°$ at the hub region. When we are going with the transonic airfoil, where my leading edge radius that's what is smaller and it is very sensitive with the incidence angle, you can safely assume near the tip that incidence as $-2°$ and near hub as $+2°$.

Same way, this deviation angle, we need to calculate based on Carter's chart. Later on based on our computational study, looking to our flow behaviour may be that can be corrected. So, when we will be doing our design, that time we will be discussing this aspect, but at this moment, now you realize, we are looking for the angles, these angles are metal angle, okay.

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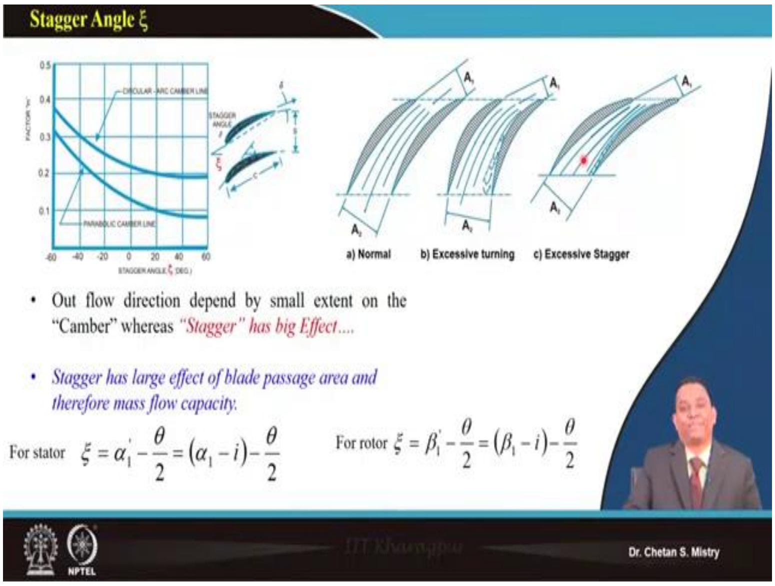

Next, because we have modified now these angles with the metal angles, accordingly we need to do modification in our stagger angle also. So, here if you look at, for stator, that's what is given by this is what is my metal angle $\alpha_1' - \frac{\theta}{2}$, same way for say rotor, we can write down like this.

$$For\ stator,$$

$$\xi = \alpha_1' - \frac{\theta}{2} = (\alpha_1 - i) - \frac{\theta}{2}$$

$$For\ rotor,$$

$$\xi = \beta_1' - \frac{\theta}{2} = (\beta_1 - i) - \frac{\theta}{2}$$

And as we have discussed, this stagger angle, that's what is very important because that's what is deciding my swallowing capacity of the compressor. So, basically how much flow, that's what is going inside my rotor, that's what has been decided or managed by this stagger angle.

Now, we have discussed about the use of different kind of camber lines. So, when we are using say circular camber line, we will be deciding with the stagger angle, we will decide what will be my 'm' parameter and when we are using say parabolic camber line, we will be selecting or deciding my 'm' parameter in a different way, okay, or vice versa also we can do with.

We need to be very careful when we are increasing our stagger angle; there may be chances that my flow will get separated from the suction surface. So basically, this is what is what we learned from our fundamental, basically we are considering our flow passage within the blade as a diffusing passage. So, all fundamentals what we have learned at the initial stage, that's what is equally applicable what we are using for say diffusing section, okay.

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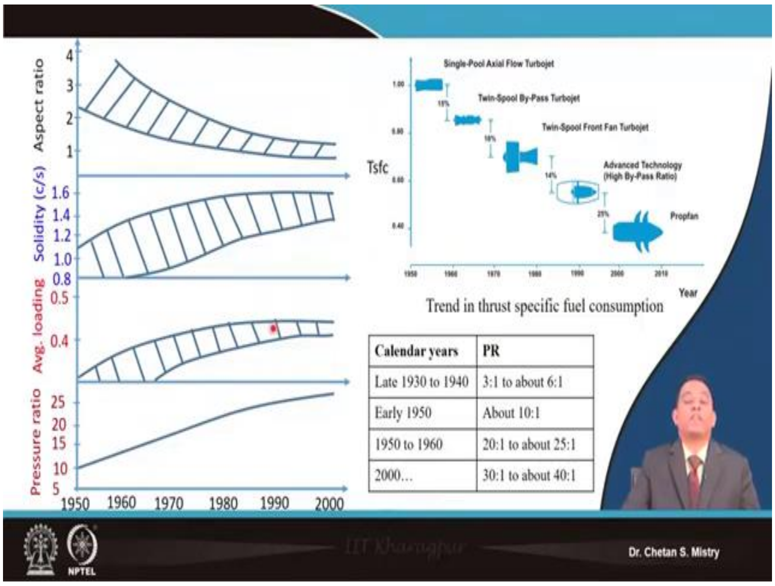

Now, this is what all we were discussing in sense of global trend for last 50 years. So, here if you look at, this is what is representing the selection of my aspect ratio and as we have discussed, now people they are going greedy and they are moving towards say lower aspect ratio; it has its own benefit and that's what is improving say my operating range, that's what is improving the stall margin with some compromise in the efficiency. But, still people, they are happy with moving towards say low aspect ratio blades that's what is having more benefit.

Now, solidity, that's what is coming into the picture that's what will be calculated based on my chord and my number of blades. You can see, over the year, people they are looking for higher solidity blades, okay. And, this is what is representing what we have discussed in last lecture, that's what is my average stage loading that is also going to increase. And all this trend, that's what is because we are expecting our overall pressure ratio that's what is going to increase.

So, you can say, this is what is the rise of my overall pressure ratio, okay, and the increase of this overall pressure ratio is not because we are looking for say a rise of overall pressure ratio, it has to concern, it has to relate with my fuel consumption. So, here if you look at, this is what is representing the global trend, okay, and we are expecting our improvement in fuel economy year by year and that's what is giving this kind of expectations from the engine. And this kind of expectations we are looking for when we are designing our axial flow compressor.

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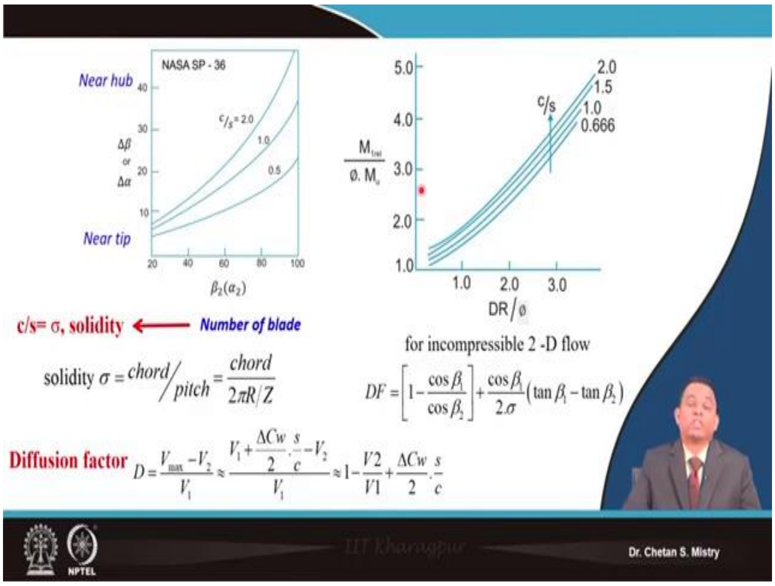

Now, the parameter, that's what we have discussed earlier also, that's what is say selection of number of blades. So, let us discuss there are different strategies they are been used for the selection of number of blades. Conventionally if you recall, we have discussed, we are having the parameter that's what is called say diffusion factor.

Now, when we say diffusion factor, at the tip region maybe you can assume your diffusion factor and from that diffusion factor maybe you can select your number of blades or you select your chord, okay. Suppose say, I am assuming my chord, based on that I will be getting number of blades and that is one of the ways of doing the calculation for the selection of number of blades, this is what is one of the ideas. And most of the time people they are preferred to go with this configuration, okay.

Now, one more strategy that's what has been discussed in NASA SP-36, it is open source document now. So, here it says we are having variation of angle say my $\beta_2 \ or \ \alpha_2$ you can realize that part and this is what is representing my $\Delta\beta$. So, based on my outlet angle and what is my $\Delta\beta$, I can select what will be my c/s, so that's what is representing what will be my solidity, okay.

$$Solidity, \sigma = chord/pitch = \frac{chord}{\frac{2\pi R}{Z}}$$

So, for particular angle and for looking for particular $\Delta\beta$, you can assume your c/s or you can get c/s value. The problem here is maybe when we are having this angle out of the range then that's what will not be coming into the decided range for the solidity and that is where you need to do your interpolation. It may lead to some changes but later on based on your calculation for the diffusion factor, you can do modification. So, this is also one of the way for the selection of number of blades based on calculating your solidity.

Remember, the solidity, that's what is varying all the way from my hub to shroud because my radius it is varying, because my pitch that's what we are defining as $\frac{2\pi R}{Z}$. So, do not forget that part, my solidity that will not remains constant from hub to shroud, that's what is always varying, okay. So, this is also one of the way for selection of number of blades, okay.

Now, this is one other approach, that's what people they have opted for; it says, it is correlating degree of reaction and flow coefficient based on inlet relative Mach number, flow coefficient and my peripheral speed Mach number, these are the numbers that's what has been plotted for different c/s.

So, here if you look at, you can do your calculation for degree of reaction for particular flow coefficient and you will be having your c/s. So, based on this also, we can do our calculation for number of blades. So, we can say, we are having different methods which are available for selection of number of blades.

So, arbitrarily we cannot select the number of blades because we have realized, that's what is having direct impact on my pressure rising capacity, it has direct impact on my stall capacity or maybe stall margin, it has also impact on say my overall performance and efficiency. So, we need to be very careful when we are selecting these number of blades. So, we can say, we have discussed about three different approaches for selection of number of blades.

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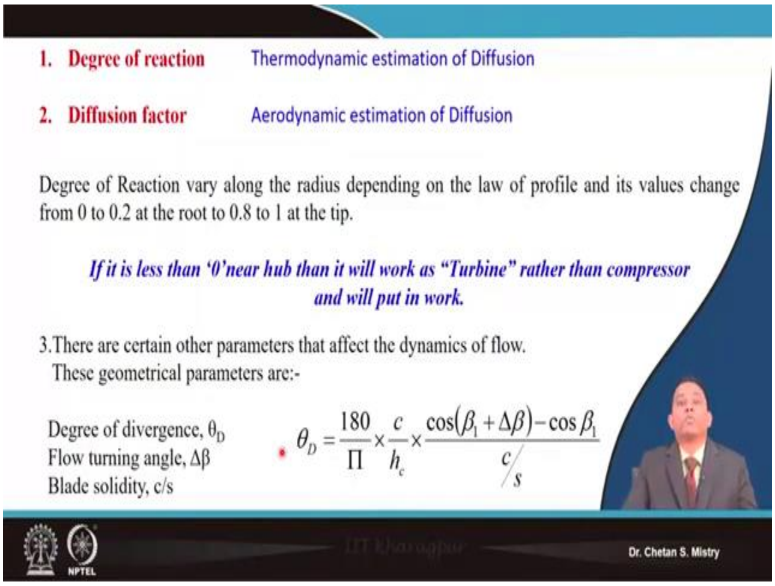

Now, let us see what all we know. We are having two parameters as we have discussed; one, that's what is called degree of reaction, we can say it is nothing but it is a thermodynamic estimation of my diffusion. Suppose, if I consider my diffusion factor, we say, this is nothing but it is aerodynamic estimation of my diffusion. So, do not get confused with these two terminologies, okay. One, that's what is representing thermodynamic aspect and second, that's what is representing my aerodynamic aspects. And if you recall, whenever we are doing our design, we are calculating both the parameters, okay.

So, what it says? My degree of reaction, that's what is varying along my span based on type of our whirl distribution what we are selecting, okay. So, it says this is what is varying from 0 to 0.2 at the root or at the hub and from 0.8 to 1 near the tip region. So, you can say, this is what is having great variation from hub to shroud.

When we say, our degree of reaction, that's what is coming to be 0, it says, it is in that particular section, that's what is acting like a turbine because that will be accelerating my flow and that's what is putting say, you know, rather having our compression to be happen that's what will be acting like a turbine and that's what will be giving you expansion work. So, we need to be very careful when we are doing our design.

So, we need to catch an eye for the variation of degree of reaction mainly near the hub region, okay. Then we have realized, since we are having our density, that's what is changing because of our pressure and that is the reason my flow passage that's what is changing all the way from inlet to outlet. And in order to take care of this variation, we have introduced the parameter that's what is called say divergence angle and we discussed that need to be within certain range, it should not be more than 8°.

$$Degree\ of\ divergence,$$

$$\theta_D = \frac{180}{\pi} \times \frac{c}{h_c} \times \frac{\cos(\beta_1 + \Delta\beta) - \cos\beta_1}{\frac{c}{s}}$$

$$where, Flow\ turning\ angle, \Delta\beta$$

$$Blade\ solidity, c/s$$

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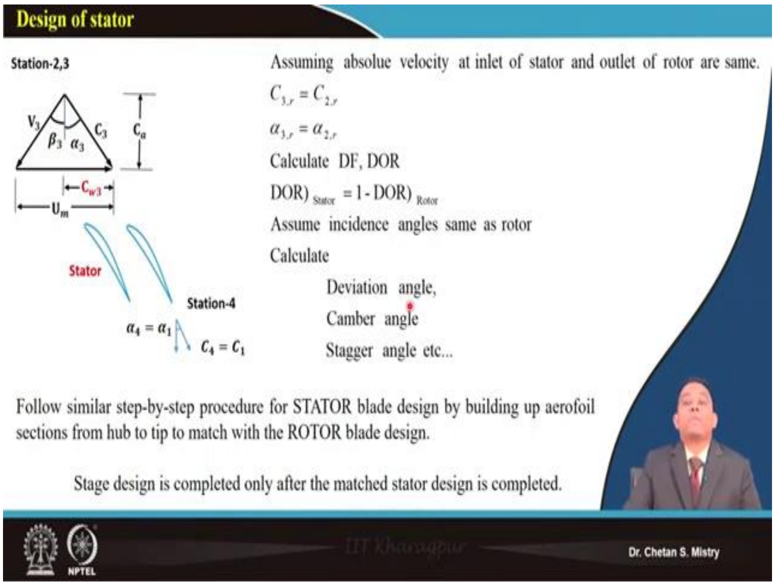

Now, all this, what all we are discussing, we are discussing about the selection of whirl distribution, we are discussing about the calculation of flow coefficient, degree of reaction, diffusion factor, all those parameters, that's what we are discussing for our rotor. So, stator also is equally important, okay.

So, when we are doing our design for the stator, we have never discussed about the design for the stator, let me introduce here, say…when we are talking about say stator design, we need to realize what flow that's what is coming out from my rotor, that's what is having say absolute velocity suppose say C_2, the same absolute velocity that will be entering in my stator.

So, it says, I can say my C_3, that's what is equal to C_2. Remember, that's what is changing with my radius. So, I am talking about particular stage or particular location, okay. And, we are assuming our absolute flow angle at the exit of my rotor, that's what is same as entry of my stator. So, that is the reason my $\alpha_3 = \alpha_2$.

Assuming absolute velocity at inlet of stator and outlet of rotor are same,

$$C_{3,r} = C_{2,r}$$

$$\alpha_{3,r} = \alpha_{2,r}$$

Now, we need to calculate our diffusion factor, we need to calculate our degree of reaction. So, if you recall, when we have introduced the parameter called diffusion factor, we said in place of angle to be β we need to select that angle as α, so that's what will be giving me my diffusion factor at particular station for particular stator.

We are calculating diffusion factor for rotor, we are calculating our diffusion factor for stator. Same way, my degree of reaction, we can say, this degree of reaction that's what will be coming say 100°. So, it says my

$$DOR)_{Stator} = 1 - DOR)_{Rotor}$$

Same way, what all we have discussed in sense of incidence angle, deviation angle, say metal angle, stagger angle, all those calculations that's what we are doing the similar way, the way in which we have done for our rotor, okay. So, this is the way in which we can do our design for rotor as well as stator.

After doing this design, we need to do, we need to check with the matching. So, it should be perfectly matched with what flow we are considering as exit from the rotor and the same flow that's what is entering inside my stator.

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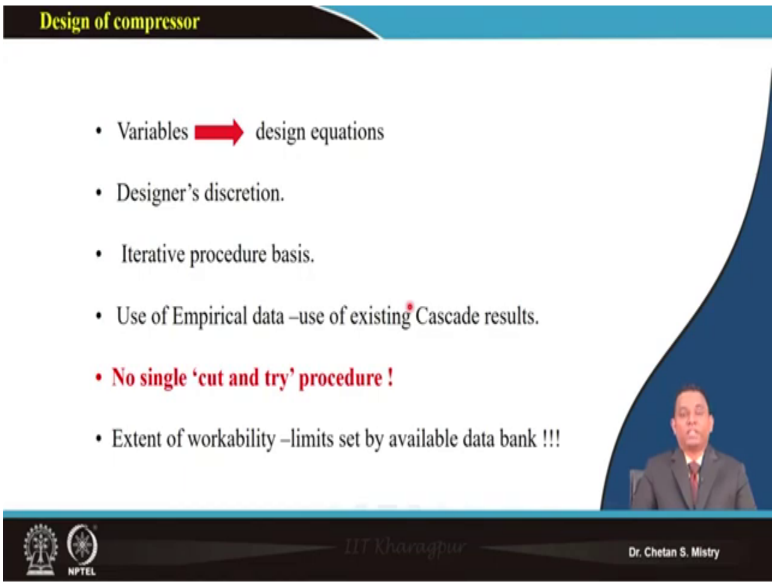

Now, in overall if we look at, say, when we talk about the design of our axial flow compressor say for particular stage or for say overall stage, we are having so many variables available. We have discussed, say flow coefficient, we have discussed stage loading coefficient, degree of reaction, diffusion factor, all those parameters, they are been based on, you know, we are having our equations, design equations.

Now, this is what is designer's discretion, it is designer who has to decide with these numbers, okay. He or she need to decide with this number, this is what is say more iterative kind of configuration, we can say, we are going with say number of iteration before finalizing our design, okay. There are many empirical correlations which are available; we are having our cascade data also available, say for engine manufacturing company, they are having their whole lot of database that's what is available for different kinds of airfoils, okay. And, this…those data which are available, they are applying for the design, okay.

So, it is not a single cut and try kind of procedure, we can say, this is what is required whole lot of understanding, this is what is required whole lot of iterations and after doing all these things you need to go with say workability.

So, you can say, we are having our now finalized with the data bank what all we are having, okay. It may be possible that after finalizing all design, aerodynamic design when we are giving that for say fabrication purpose, maybe fabricator or mechanical engineer may be having some limitations, again he or she will be asking you for the modification in design and that's what will be very challenging. So, this is what is, you know, it is like more in sense of iterative designs. Many times, people used to say blade design is art, okay, it is art rather than science, many times.

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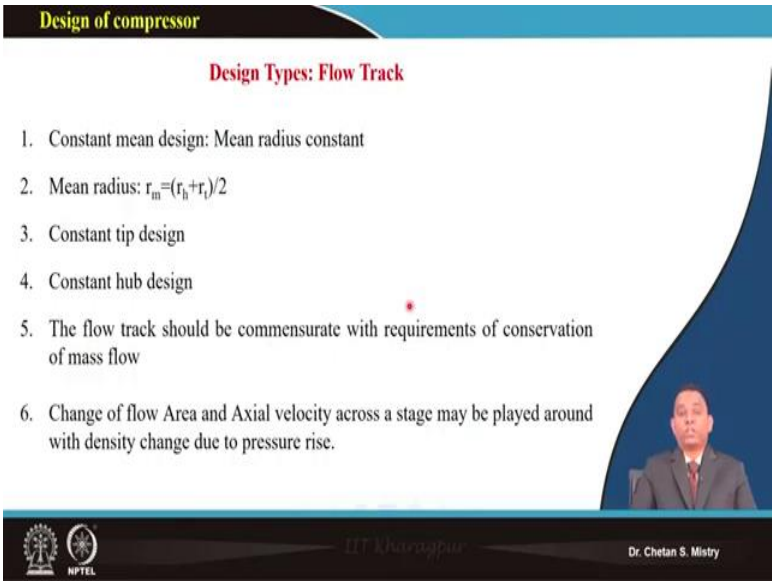

Now, we have discussed about the flow track design, we have different options available with us, we can go with the combination of different flow track designs, all these things that's what we need to be very careful when we are doing our systematic design for HP compressor, when we are doing our design for say LP compressor. So, the flow track selection that is also a very important parameter as we have discussed earlier.

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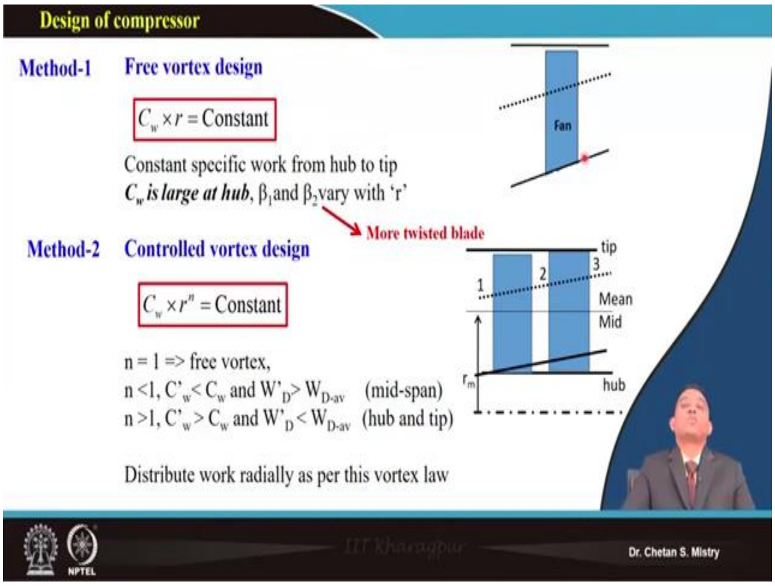

Now, when we say, we are having our design. So, very important thing at mean section you will be doing all your calculation, later on we will be opting for different design strategies, say based on say whirl distribution, that's what is happening; we are going with say maybe free vertex design, we are going with say force vertex design, maybe we will be going with say constant reaction design, there are different possibilities we have, okay.

So, it says when we are going with say free vertex design, we have discussed that may be having constraints in sense of highly twisted blade. Remember one thing, when we are doing our design for say low speed compressor, our inlet diameter and outlet diameter they both will be same. So, my mean line calculation that's what we are doing at the mid station.

When we are going with the transonic kind of configuration, suppose say my fan, under that condition my inlet area and outlet area, that will be different because I am having high pressure rise and that is the reason why my density change will be very large. When we are doing that kind of design, we need to select our mid station as 75% of span, do not forget that part, okay.

At the same time, we need to divide this inlet station and outlet station in equal number of parts. Suppose say, I am taking say, 10 station at the entry, I will be taking 10 station at the exit and that is how we are doing our design.

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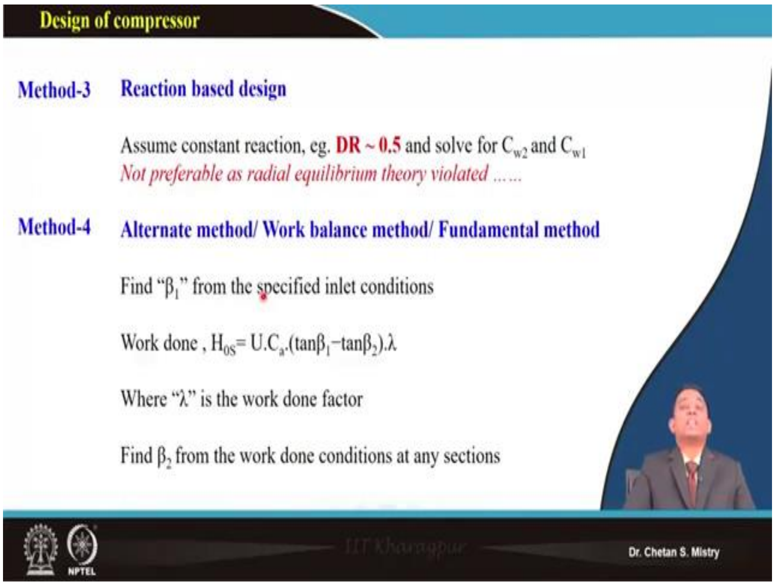

So, you know, we have discussed about say constant reaction design, what it says? It is not preferred because we are having limitation; it is not satisfying our radial equilibrium equation. And, that's what will lead to have deterioration in the performance. We also have discussed about our fundamental method and that fundamental method that's what is giving so much of flexibility in sense of selection.

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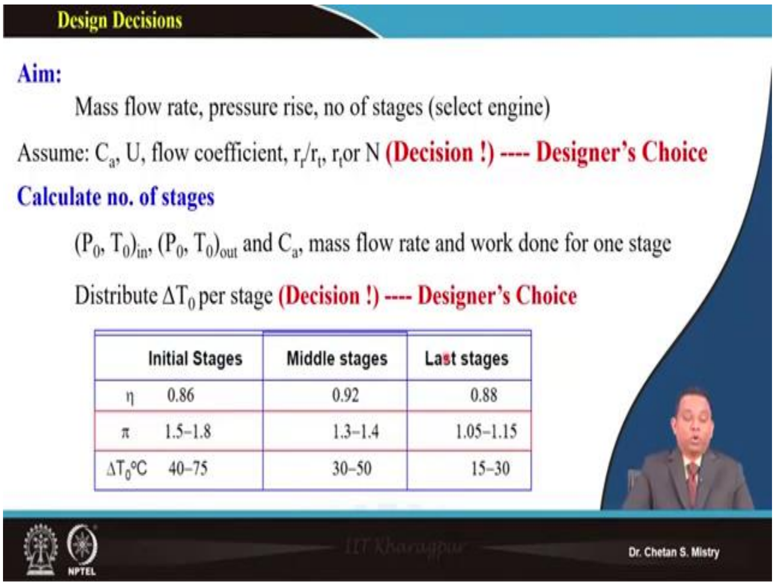

Now, you know, like, as designer what we are expecting, is you know, to select different parameters; and we have realized, the selection of parameter that's what is very important based on what thrust we are looking for or what power we are expecting from say particular engine. So, the selection of parameters like mass flow rate, pressure rise, number of stages, that's what is based on which kind of engine we are designing with or say which kind of engine where we will be using this axial flow compressor.

So, maybe we need to assume with axial velocity, maybe we need to assume with my peripheral speed, we need to assume say flow coefficient, maybe radius ratio, tip radius or say my rotational speed. So, this all decisions they need to be made by the designers, okay. So, it is not many times the design may not be straightway what we are expecting, which stage you are designing, that's what is very important. So, you need to make necessary designs. So, it says this is what is designer's choice, okay.

Now, we need to decide with the number of stages as we have discussed; when we are deciding this number of stages, that's what is based on what all we have discussed about per stage pressure rise and this is what will be giving us what will be my distribution, okay. So, you can say for initial stage, you can go with high pressure ratio but at the same time your efficiency will be lower.

When we are going with the middle stage, you can go with moderate pressure rise and at the same time efficiency will be larger. And, if you are looking for say later stages, we will be having compromise in sense of efficiency as well as in sense of my pressure rise. So, this is what will give some of the idea for the initial guess.

So, again here, this is what is the designer's choice; he or she need to make the decision what per stage pressure rise they are expecting, what polytropic efficiency they are expecting from the stage. So, this is what is coming with the designer's choice. Over the year with the experience, people, they are selecting these numbers to be safely and that's what will reduce the number of iterations what they are going with, okay.

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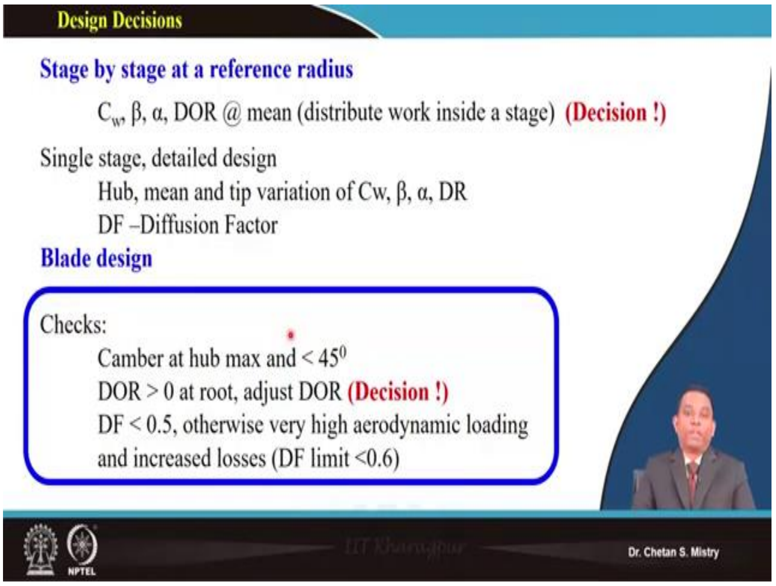

Now, when we are going with say stage to stage, we are calculating our whirl velocity component, we are calculating our β angle, we are calculating our α angle, we are calculating our degree of reaction; at mid station, sometimes we are assuming our initial guess of degree of reaction. So, kind of whirl distribution what we are selecting that is also designer's choice, which kind of vortex distribution he or she is looking for, okay.

So, you have your whole lot of flexibility in sense of design. So, for single stage design, we will be doing all our calculation in sense of different flow parameters or initial guess parameter what all we have discussed; there say, degree of reaction, diffusion factor, stage loading coefficient, your peripheral speed, all those things, that's what we can decide with and we can calculate, that is also the choice of designer.

Now, when we are coming with all these designs, we need to be very careful here, this is what is check. When we finish our design, we need to check with what is happening. It says, my camber angle at the hub, it should not be more than 45°. If this is what is your case, you can say, aerodynamically your design will be more challenging, your losses will be very high and what pressure rise you are expecting may not get or maybe you will be having loss of efficiency.

So, we need to take care my camber angle should not increase by 45°. You can say, my $\Delta\beta$, that's what should not be increased by this number.

Next check, that's what is your degree of reaction always need to be greater than 0. We have seen, when we are doing our calculation, it may be possible that degree of reaction will be going 0 or may be negative. So, under that condition, it is designer's choice to modify that degree of reaction near the hub region; otherwise, that is also lead to give your flow separation that's what will lead to loss of efficiency, so we need to be very careful about this aspect.

Next parameter, it says my diffusion factor and as we have seen, we have discussed, Lieblein, he has discussed, he said like my diffusion factor that should not be greater than 0.5, but with current trend of expected pressure rise to be very high, per stage pressure rise to be very high; it says, people, they are safely they are taking this diffusion factor in the range of 0.6.

So, this is what is all giving…what all need to be our design strategies. Now, I am sure, with this understanding of last few lectures, we have understanding…detailed understanding how do we proceed with the selection of different parameters, after selecting those parameters how do we proceed with say design, then after doing design or during design how do we decide with the parameters that's what we will be taking care in the initial design stage only so that we will receive what we are expecting in sense of our pressure rise, in sense of our efficiency, in sense of our overall operating range. So, here we are stopping with.

Now, from next lecture, we will be discussing about the design of low speed axial flow compressor, where we will be discussing about all this parameter calculation and then we will be checking with whether it is coming in the range or not. Stay with me and enjoy this course. Thank you, thank you very much!