Aerodynamic Design of Axial Flow Compressor & Fans
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Lecture 20
Design Concepts (Contd.)

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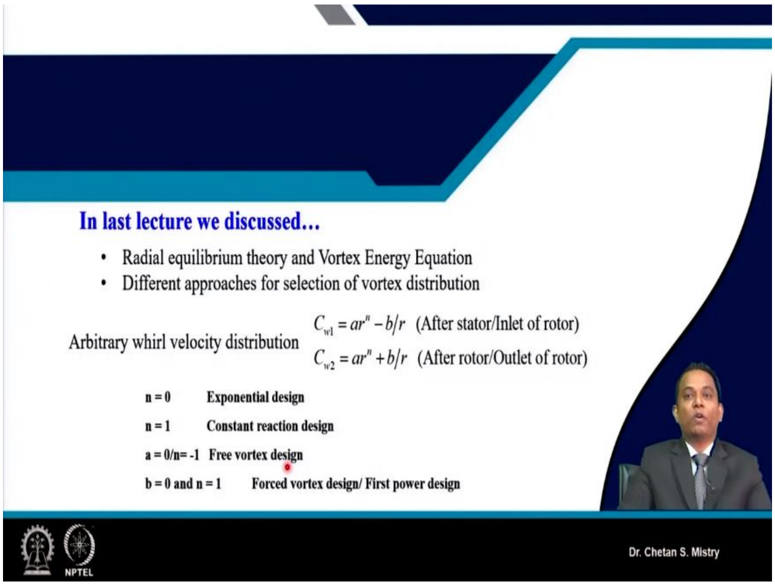

Hello, and welcome to lecture-20. In last lecture, we were discussing about radial equilibrium theory, we were discussing about vortex energy equation. We must realize, what all are the importance of these two, in sense of our design, okay. So, we have, we were discussing about say different approaches for the selection of vortex distribution.

And we have realized, if we are considering our $C_w \cdot r = constant$, that's what is we are defining as a free vortex design. And later on, we have started discussing about the selection of vortex, that's what we say arbitrary whirl velocity distribution. And if you look at, we have discussed what needs to be a whirl at the entry, we can say it is given by $C_{w1} = ar^n - b/r$.

And at the exit of my rotor, we can consider $C_{w2} = ar^n + b/r$. So, based on that we were started discussing about what all will be the change in our design, when we are considering different exponents, that's what is a value of 'n'. So, if you look at, say, for this previous arbitrarily considered vortex formula, if you are considering our $n = 0$, that's what we have discussed as the exponential design.

And for that exponential design, we have come up with some conclusion in sense of how my degree of reaction that's what is varying and how my axial velocity, that's what is changing.

When I am considering my $n = 0$ consideration. Then we started discussing about $n = -1$ configuration, where we say, that's what is nothing but it is our basic equation in the formulation of say…our free vortex design, then we were discussing about $n = 1$. And that's what we have defined as say our force vortex design, or say first power design.

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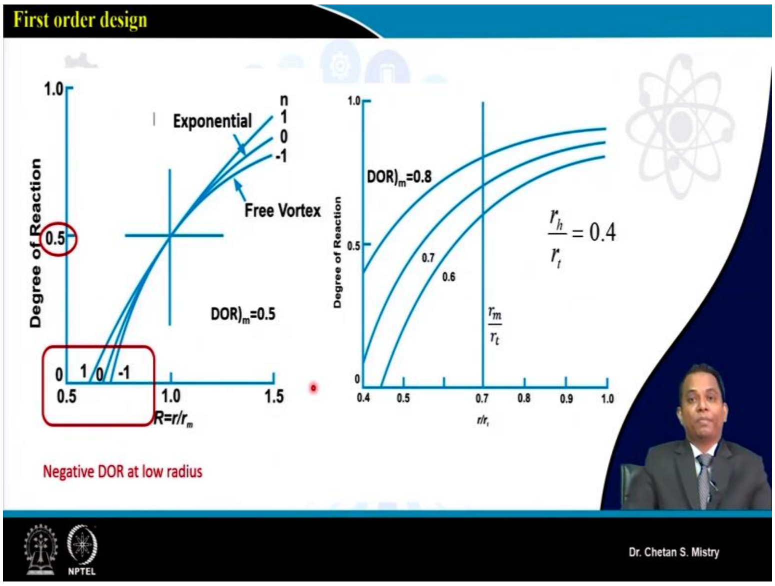

Now, if you recall, in last lecture, we were discussing about the plot. This is what is a plot, that's what is representing how my span wise degree of reaction, that's what is varying, if we are taking different exponent values. Say, if we consider as we discuss $n = -1$, that's what is representing my free vortex design.

So, somewhere in the mid-section, we can say, we are having our degree of reaction to be 0.5. And if we will try to move towards our hub. So, if you look at, towards my hub, my degree of reaction, that's what we will be having, say value to be 0. Or if we have moved further, if we extend that on the negative axis, maybe at the hub, we will be having our degree of reaction to be negative.

And if we consider our $n = 0$ configuration, where it says my degree of reaction, that's what is having considerably higher value. And if we consider our $n = 1$, that's what is given our say, degree of reaction variation to be large. But for all of them, if you look at near the hub region, there are chances that we will be having our degree of reaction value to be going to be negative.

Now, as we have discussed, say, when we say our degree of reaction, that's what is going to be 0, then we can say there is no diffusion work, that's what has been done by my rotor. So whole diffusion that will be happening for the stator. And when we say our degree of reaction to be negative, that's what is representing in spite of having diffusion to be happened at particular station, we will be having the flow acceleration that will be happening there.

So, in spite of that section, it should act like a compressor that may work like a turbine. So, that's what will lead to increase in losses. When we say our increase in losses, that's what will be reflecting in sense of our pressure rise as well as in terms of our efficiency. So, we will be having loss of efficiency by few points, if we consider when we will be having negative degree of reaction.

So, in order to get rid of this situation, what we think? Let us see, suppose if I consider, my degree of reaction at the mid station we will be selecting at a different value. Suppose if I consider my degree of reaction, I am increasing from 0.6 to say 0.8. And, that's what is realizing that when I am increasing my degree of reaction to be higher value, the chances for my degree of reaction to go in negative value or maybe 0 value, they are less.

So, now the question is, this is what is giving us hint, like, can we think our design in a different way? Yes, you are thinking in the right way, let us assume. let us think of having degree of reaction to be constant throughout my span, that's what is our next design approach.

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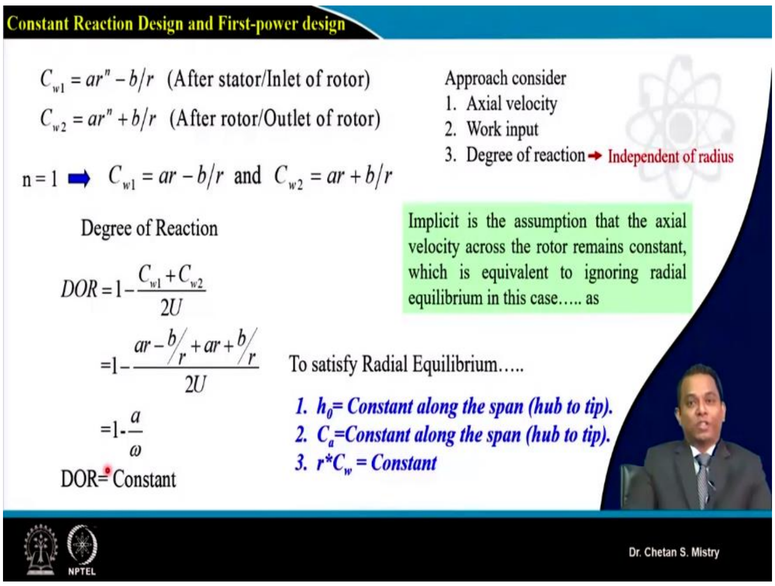

So, here if you look at, this is what is we have discussed as arbitrary distribution of my whirl component after a stator or at the entry of my rotor; we can $ar^n - b/r$ when we are considering after rotor, that's what is $ar^n + b/r$, okay. Now, if we consider our value $n = 1$, that's what will be giving me my value of distribution of C_{w1} and C_{w2}.

Now, what we know, in order to have our flow to be three dimensional and we consider our flow to satisfy our radial equilibrium, we need to satisfy three different criteria. So, let us recall, we have discussed my stagnation enthalpy that need to be constant throughout my span; say from hub to tip, my stagnation enthalpy need to be constant or we can say or work input need to be constant throughout my span.

Second requirement as we have discussed, my axial velocity need to be constant throughout my span and third we have discussed, it need to come up with my whirl distribution as $r \times C_w = constant$. Now, here in this case, what we are assuming? We say our degree of reaction, that's what is constant throughout my span, that means my degree of reaction is independent of my radius.

Now, the question is what we are expecting in sense of satisfying our say radial equilibrium theory, we are moving towards away from that kind of requirements. What it says, if we are considering when we are having this constant reaction kind of configuration, say assumptions what we are making in sense of our axial velocity to be constant, that may not be coming, okay.

So, if you look at suppose if I put my degree of reaction formulation, that's what is $DOR = 1 - \frac{C_{w1}+C_{w2}}{2U}$ if I will be putting my numbers C_{w1} and C_{w2}, it says my degree of reaction, that's what is coming to be constant. So, that's what is our design requirement.

Now, if you recall, in last lecture, we were discussing; in order to have this radial equilibrium theory, we can have different kinds of design thought process. In which we were discussing, if we know two of the parameters or we assume to of the parameters to be constant, we can easily calculate our third parameter. So, same approach we will be using for this design concept, say for constant reaction kind of design.

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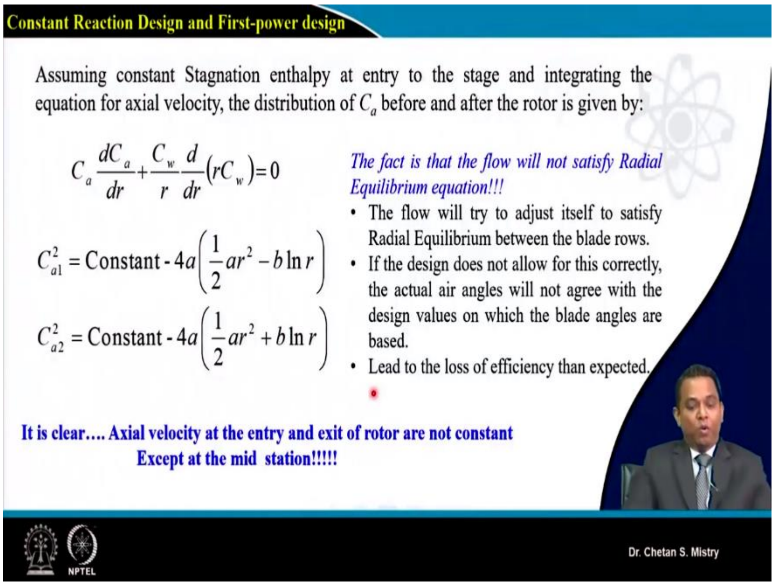

So, here, let us assume, say constant stagnation enthalpy at the entry of the stage. And if we are integrating that, we will be getting, using our vortex energy equation, we will be getting the formulation for my variation of axial velocity.

$$C_a \frac{dC_a}{dr} + \frac{C_w}{r}\frac{d}{dr}(rC_w) = 0$$

$$C_{a1}^2 = constant - 4a\left(\frac{1}{2}\,ar^2 - b\ln r\right)$$

$$C_{a2}^2 = constant - 4a\left(\frac{1}{2}\,ar^2 + b\ln r\right)$$

So, if you look at, this is what is our vortex energy equation in which if I will be putting, say $C_w \cdot r$ value, that’s what is giving me my axial velocity at the entry, that’s what is some $constant - 4a\left(\frac{1}{2}\,ar^2 - b\ln r\right)$, same way at the exit if you are looking at you will be getting your axial velocity to be different.

So, now the situation is when we are considering our constant reaction design, it says at the entry of my rotor and at the exit of my rotor, my axial velocity, that’s what is varying, it is varying with my radius. So, you can say, this is what is violating our radial equilibrium equation, okay. Now, the thing is, the question may come in our mind, what if it is not satisfying the radial equilibrium equation?

So, if you try to look at, suppose if we consider, say my radial equilibrium it is not getting satisfied. So, what happens? My flow at the entry, it will adjust itself in such a way that it will try to satisfy radial equilibrium between the rotor passage, just realize this thing. It says like, we are imposing, we are forcing a fluid particle to follow the radial equilibrium, okay.

Now, suppose this is what is your situation, what will happen? We have already been done our calculation for flow angles, we have done all our calculation for our velocity components. Now what is happening? Because, it is not satisfying my radial equilibrium, so my flow that will incident on my blade and the angle at which my flow will be coming out, that may go different from my design requirement, or for what I have designed.

Now, if this is what is your case, you can say your rotor, that's what is going to be working under more of design condition. And if this is what is working in that kind of situation, you can say, we will be having some losses, those prone to be happen. And when we say, these losses, that's what is happening inside, and, that's what will be leading to reduction in my efficiency; because, I will be having increase in my losses.

So, that is the reason why when we say we are adopting my constant reaction design, that's what is not satisfying radial equilibrium equation. And if it is not satisfying our radial equilibrium, you know, we have more challenge in sense of what we are doing. Now, with present availability of computational tools, it will give a rough estimation, rough idea of what is happening with our flow.

And that's what will be helping designers to modify some changes that can be incorporated in order to meet the requirements. But you can understand, this is what is more challenging in sense of addressing what we are looking for. Because, as we have discussed, the Aero Engines, which are made up of this kind of axial flow compressors, they need to meet so many requirements, specifically when we are talking about application for Aero Engines.

Suppose if I consider these Aero Engines we are using for commercial purpose, their requirements are different and when we say, when we are applying these for a military purpose, there the expectations are so high, that's where the designs, that's what will be coming into the picture as a major challenge, okay.

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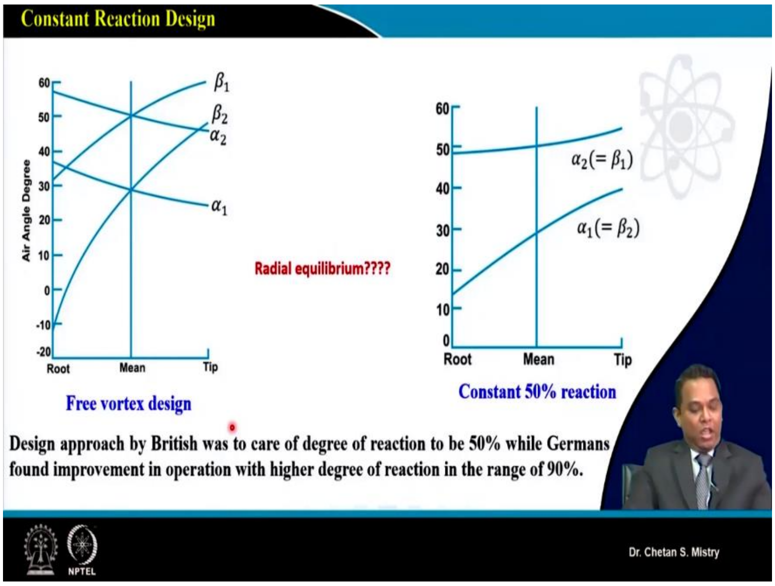

Now, let us try to compare these two configurations; suppose, if I consider conventionally we are discussing about the free vortex design. So, here this is what is representing how my angles that's what will be varying from say hub to tip. And, as we have discussed, if you look at near the hub region, we will be having say great variation of blade angle or blade deflection angle.

So, if you look at near the hub, my $\Delta\beta$ will be large and if you look at near the tip region, my $\Delta\beta$ is going to be slightly lower. But, if you look at in overall sense, this is what is giving me highly twisted blade. Now, there is nothing wrong in getting highly twisted blade, but realize one thing, when we say we are having highly twisted blade, that's what is putting challenge in sense of fabrication of those blades, firstly.

Secondly, if you are looking at, what it says nearby hub region, my deflection - flow deflection will be very large, that means, it needs to do whole lot of work in that particular region. Suppose if I consider my degree of reaction to be lower or says 0, then we have discussed, whole my diffusion work, that's what will be happening inside my stator. So, you know, for this kind of configuration, design for stator will be becoming very challenging.

Lot of research, that's what is going on in order to address the issue, that's what is called hub stall, okay. So, when we are having this kind of design configuration, yes, this is what is a major challenge. So, do not get confused with highly twisted blade. You will say with present availability of machining, it is possible to design or to fabricate this kind of blades.

Yes, but you can say, when I will be having a highly twisted blade, my flow three dimensionality will be very large, okay. And, we have seen, if I will be having my blade to be highly cambered, suppose my $\Delta\beta$ is large near the hub, there are more chances for my flow to get separated from suction surface. And, that's what we have defined as a stall. And as I told, that is what people used to define as a hub stall.

Now, looking to this, we have opted for say next option, that's what is called constant reaction design. So, here if you look at, this is what is representing how my angles will be varying along my span for 50% reaction design. So here, if you look at, compared to this case, if we are designing same configuration, it says my $\Delta\beta$ near the hub, that's what will be coming to be lower. And at the same time, my $\Delta\beta$ at the tip, that's what is coming to be slightly higher.

So, if you compare these two; it says my blade twist will be lower for say constant reaction design. But now as I discussed, we have our challenge with what we say it need to be satisfied the radial equilibrium theory. So, that's what is a question mark for the designers, but even if you recall, when I was discussing about the degree of reaction, that time I told, like designers say from British, they used to put say degree of reaction to be around 50% at the mid-section, okay, they are opting for a constant reaction design, also.

For most of the German designs, as we have discussed, they are having high degree of reaction that may be ranging in the range of say 90%. So, you will be having a whole lot of diffusion, that's what will be happening only in rotor and my stator will be guiding the flow. So, this is what is a challenge. So, now you... I am sure, you must be realizing, like what is the importance of calculating degree of reaction, okay.

So, the course it has been designed in such a way that the step by step you will be moving and by moving and understanding, you will be getting more knowledge more understanding, then you are going towards more complexity. And again, you are trying to gain the knowledge, again, you will be going in more complexity. And that is how, at the end of this course, you will be able to understand what all are the importance of these numbers.

Because, in books or what all you are learning, people, they will be given these numbers but that numbers, they are having special meaning and that's what as a designer we must understand.

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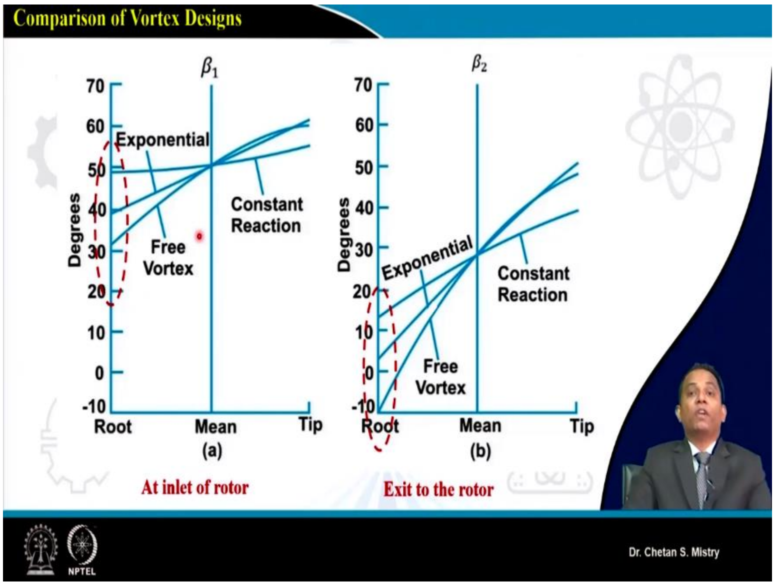

Now, here if you look at, this is what we were discussing in sense of change of angle at the entry of my rotor and at the exit of my rotor. So, here if you look at, as we have compared these three cases; say free vortex, say the constant reaction design and we consider say exponential design. So, if you look at carefully, it says when you are having say your degree of reaction to be say constant reaction design, if you are opting for, that's what is giving me my variation of $\Delta\beta$ to be lower, and you will be having highly twisted blade with free vortex design configuration.

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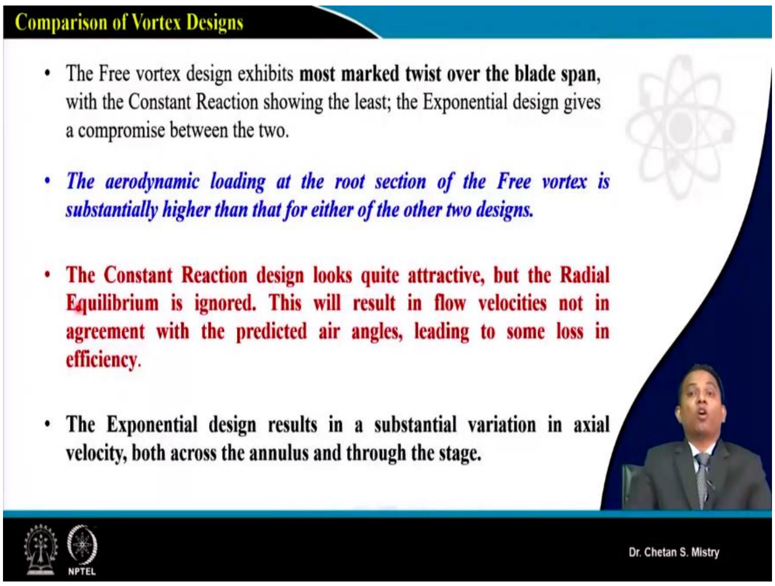

Let us have a look at, say what all we learn, what all we understand here, what it says? My free vortex design what we have discussed, that's what will be giving me highly twisted blades and constant reaction, that's what is giving say less, and if we put say exponential design approach, that's what will be the compromise between these two cases, okay.

So, many times rather going with say constant reaction design, people they have preferred to go with exponential kind of design, it is all designer's choice, you have so much flexibility. Because, just realize one thing, there is no systematic way of doing design, this is what all is coming with what all you have in sense of special requirements.

And you need to understand those requirements and accordingly you need to start doing your design, okay. Next what it says? My aerodynamic loading at the root section for free vortex is substantially higher. And that's what will be, we were discussing, that's what is a challenge in sense of doing the design because that is where I will be having more chances for my flow to get separated. At the same time, the design of stator for that particular station, also will be very challenging, okay.

So, constant reaction design, it says, it looks more attractive; but, if you look at, it is not satisfying your radial equilibrium. And that's what it says, there may be possibility that your rotor, that will be going off design way and that's what will not give what… what efficiency you are expecting for this machine, because of induction of my losses, okay.

Now, exponential design, if you look at, that's what is having challenge in sense of variation of my axial velocity, and that's what is across the stage as well as near the annulus. So, you know, like, this is what is giving you whole lot of options for the design, but it is you to decide, how you will be approaching with your design aspects, okay.

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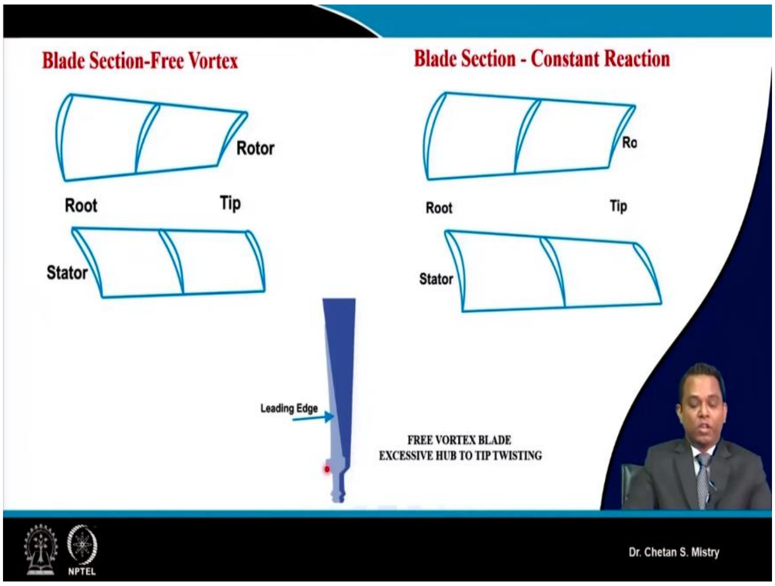

Now, here, this is what you can look at, this is what is representing the blade sections four three vortex design and this is what is representing my blade section for constant reaction design. Here, as we have discussed near the root region or near the hub, we will be having a whole lot of deflection, that's what is happening.

So here, I will be having my blade to be more have more turning. Just look at, if you compare for constant reaction, my blade turning will be comparatively less, okay. And here if you try to look at for stator as we discussed, if we are looking for axial exit, it will need to turn the flow in a great angle way. So, this is what will be the stator, in line to that, here, we will be having stator like this.

So, here if you look at, this is what is showing one of the blade and for that blade, if you look at, we will be having say highly twist. So, here near the hub region, if you look at, we are having say higher $\Delta\beta$, near the tip region we are having lower $\Delta\beta$, okay. So, now, you can understand, we are having different approaches for the design of the blade, okay. With our understanding, we need to move ahead with what all options you will be opting for, okay.

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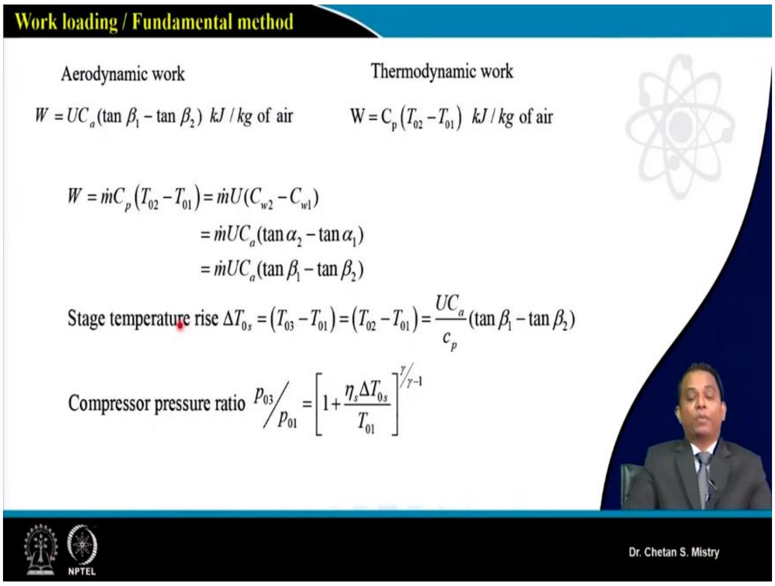

Now, let me discuss some other kind of approach with special thought process. That's what I say as a fundamental method, or we can say is a work loading method. Now here, what we learn from our fundamentals, we are having our aerodynamic work, that's what is correlating my work in sense of my speed, axial velocity and my $\Delta\beta$ or we can say, whirl component, okay.

And, we are having our thermodynamic work, that's what we are representing in sense of T_0 $C_p \cdot \Delta T_0$, or we can say $h_{02} - h_{01}$, okay. Now, let us try to look at, fundamentally what we have understood, my aerodynamic work and thermodynamic work, they both need to be same. Let me equate here.

$$W = \dot{m}C_p(T_{02} - T_{01}) = \dot{m}U(C_{w2} - C_{w1})$$
$$= \dot{m}UC_a(\tan\alpha_2 - \tan\alpha_1)$$
$$= \dot{m}UC_a(\tan\beta_1 - \tan\beta_2)$$

If I will be putting like this, I will be getting my stage temperature rise, that's what is a function of my peripheral speed, my axial velocity, I will be having my $\Delta\beta$, that's what will be coming into the picture.

$$Stage\ temperature\ rise\ \Delta T_{0s} = (T_{03} - T_{01}) = (T_{02} - T_{01}) = \frac{UC_a}{C_p}(\tan\beta_1 - \tan\beta_2)$$

And if you recall, when we were discussing our fundamental understanding, that time also we have discussed what all are the ways to improve or to increase your pressure ratio? So, let me introduce that pressure ratio, it says, that's what is given by

$$\mathit{Compressor\ pressure\ ratio,}$$
$$\frac{p_{03}}{p_{01}} = \left[1 + \frac{\eta_s \Delta T_{0s}}{T_{01}}\right]^{\frac{\gamma}{\gamma-1}}$$

So, this is what is representing my stage pressure ratio, okay.

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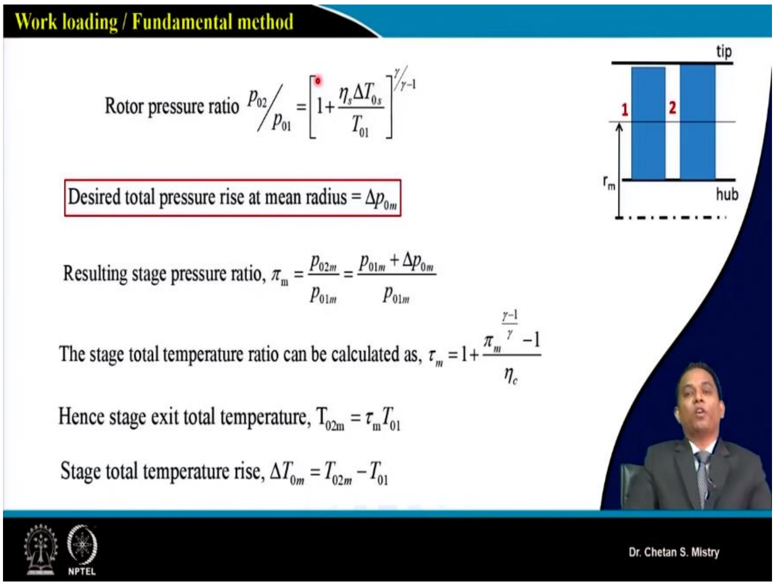

Now, let me rewrite this equation in sense of my pressure ratio for the rotor. That's what I am writing as p_{02}/p_{01}. So, this is what is my station 1, and this is what is say my exit station 2. So, for that, we can write down this as a equation.

$$\mathit{Rotor\ pressure\ ratio,} \frac{p_{02}}{p_{01}} = \left[1 + \frac{\eta_s \Delta T_{0s}}{T_{01}}\right]^{\frac{\gamma}{\gamma-1}}$$

Now, let us try to understand this design aspect or design perspect in a different way. I will say, I am looking for my rise of pressure at the exit of my rotor, okay.

So, I say, some amount of Δp_0, that is what I am expecting at particular station at the exit of my rotor. So, let me write down say my p_{02}, that is nothing but my pressure, I am expecting at station 2, at the exit of my rotor, that's what I can write down $p_{01} + \Delta p_0$, okay. If this is what is your case, you can write down your modified case or modified pressure ratio at the mid station as say, p_{02}/p_{01}, that is nothing but my $\frac{p_{01m}+\Delta p_{0m}}{p_{01m}}$, okay.

$$Resulting\ stage\ pressure\ ratio, \pi_m = \frac{p_{02m}}{p_{01m}} = \frac{p_{01m} + \Delta p_{0m}}{p_{01m}}$$

Now, based on this, we can calculate what will be our temperature ratio, and what will be my exit temperature at that particular station. So, that's what I am writing as say total temperature rise at that particular station, that's what we are writing as say

$$\Delta T_{0m} = T_{02m} - T_{01}.$$

So, this is what is my ΔT_0 at that particular station. Just understand this is what is say, you know, what all we know and from that we are trying to move towards a new approach for the design.

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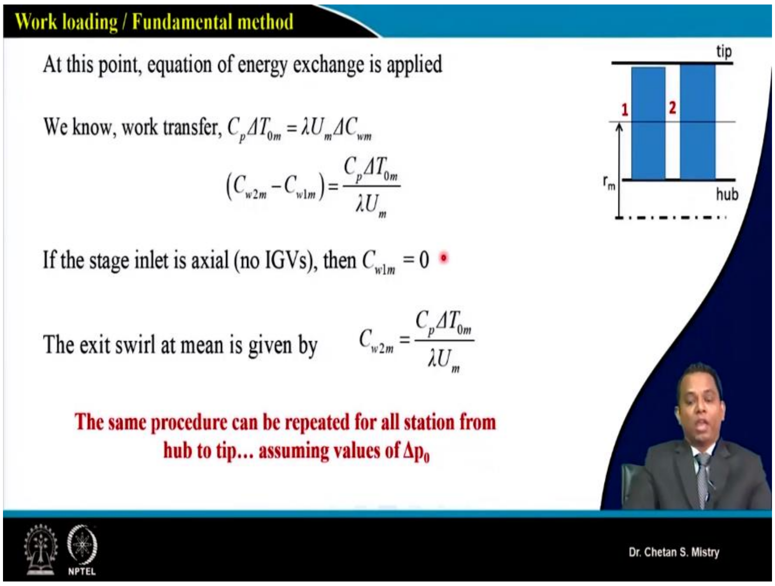

Now, what we learn? We are having the case, say aerodynamic work and thermodynamic work, they both need to be same. If that's what is your case, we can write down this in sense of say change of my tangential velocity component as say

$$We\ know, work\ transfer, C_p \Delta T_{0m} = \lambda U_m \Delta C_{wm}$$

$$(C_{w2m} - C_{w1m}) = \frac{C_p \Delta T_{0m}}{\lambda U_m}$$

Suppose, if I consider, my tangential velocity component at the entry, suppose I am not having inlet guide vanes.

Now, you realize that part. So, I can say my C_{w1} at the entry is 0 and that's what will be giving me what will be the change of my whirl component at the exit at mid station. So, at this particular station, I can calculate what will be my C_{w2}, okay. Now, this is what we have done calculation at particular station.

$$If\ the\ stage\ inlet\ is\ axial\ (no\ IGVs), then\ C_{w1m} = 0$$
$$The\ exit\ swirl\ at\ mean\ is\ given\ by\ C_{w2m} = \frac{C_p \Delta T_{0m}}{\lambda U_m}$$

Now, the same logic you can apply by incorporating Δp_0 at different stations, okay. You can recall, if I consider the rotor blade and stator blade, it is made up of number of airfoils. So, I can say, they all are the working stations. So, at all those working stations, you can assume now Δp_0 and you can do your calculation what we say in sense of your C_{w1} and C_{w2}, okay.

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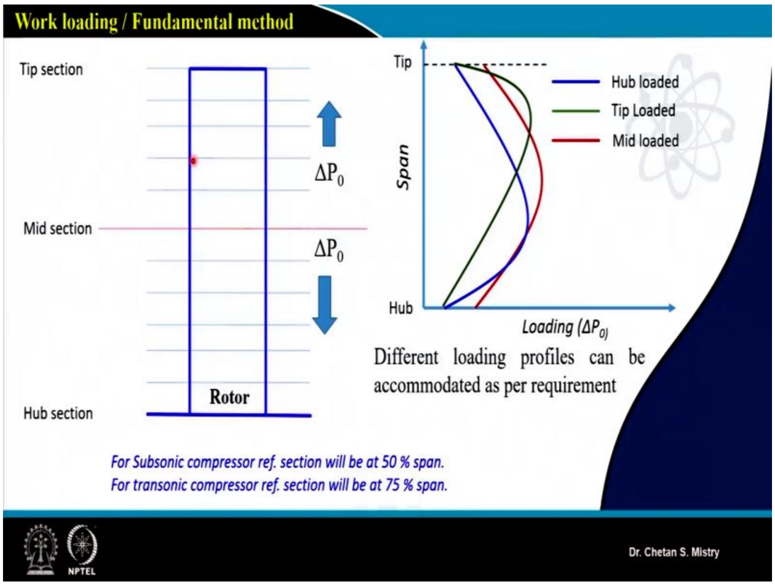

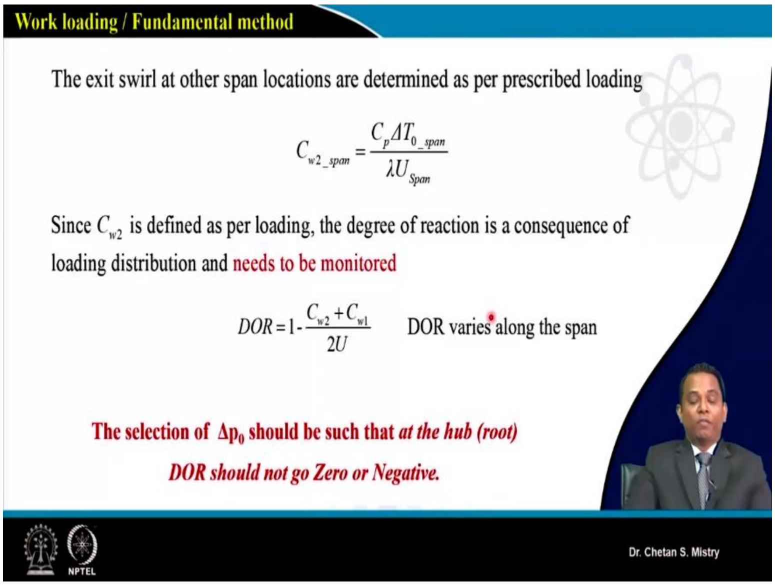

So, let me put it here, suppose if I consider at this station, at mid station, we have done our calculation, that's what will be giving me what is my β_2 that's what is giving me what is my β_1; that's what is my requirement, you can say, that's what is my $\Delta\beta$, okay. Now, I can as assume my Δp_0 from mid-section to hub-section; same way, I can assume different values Δp_0 from mid-section to tip-section, and at all station, using this formula, you can calculate what will be your $\Delta\beta$, okay.

So, this is what is say your unique design approach what we say. Now, you can say, at different station as we have discussed, we can calculate what will be my swirl component and once, we are calculating what is our C_{w1} and C_{w2} at particular station, based on our fundamental understanding, we are able to calculate what we say, my degree of reaction, okay. So, if I say, my degree of reaction, that's what if I will be putting, you can say my C_{w1}, that's what is, suppose say, if it is axial entry that is 0, and you can say this is what is my C_{w2}.

If that's what is your case, it says, my degree of reaction, that will be varying along the span. So, that's what is varying with my radius. Again, what is a requirement? We need to check what is happening with my degree of reaction at hub! Suppose if I consider my degree of reaction is coming to be 0, that's what we do not want.

We do not want our degree of reaction to go negative. What will you be doing? For that configuration, here, near the hub station, you select your Δp_0 in such a way that your degree of reaction will not go negative or it will not go 0, that's what is giving very good flexibility in sense of doing our design, okay.

So, here if you look at, this is what all we were discussing about, say at mid station, what pressure rise I am expecting, that's what will be giving me idea, like what Δp_0 I will be assuming at the mid station and according I will be varying my Δp_0 from mid-station to say hub station or hub-section and from mid-section to my tip-section.

Now, here in this case, you are having the flexibility in the design. So, here if you look at, this is what is representing how you can assume your Δp_0, okay. So, here if you look at, this green line, that's what is representing if I am opting for the approach of tip loaded rotor, okay. So, I will be having higher Δp_0 that need to be assumed near my tip region. I can even go with say high hub loaded design, say this is what is my design, that's what is representing hub loaded design. Even I can opt for, say mid-loaded design.

So, you know, like this is what is approach, that's what will be giving you so much of flexibility in sense of doing your design, which may not be possible with what all approaches we are discussing with. And if you recall, we were discussing say for recent trend, people, they are assuming different exponents, that is what say… overloaded and under loaded configuration. So that's what will be in line to this.

So, you know, like this is what is one of the approach, that's what I am preferring for my designs. So, what all designs we are doing at IIT Kharagpur or throughout my career what designs we have done, that's what is based on this fundamental approach and we are so confident of this design, because that's what is giving what all we are looking for in sense of performance, okay.

Now, we will be discussing this approach again when we will be started discussing about our designs for low speed compressor, we will be discussing again this when we will be discussing about design of say high-speed compressors. It says, when we are designing the subsonic compressor, my reference station will be considering at 50% span, okay. So, this is what we are considering as our initial design plane.

When we are designing transonic compressor or say supersonic compressor, then, that initial design we are doing at 75% of span, okay. So, in overall, if you try to recall, we have discussed about all design approaches which are available in open literature which people they are opting for their design, we have discussed about the exponential design, we have discussed about the free vortex design, we have discussed about the constant reaction design and we have discussed about what all are the advantages and limitations of those methods.

Then we have come up which say fundamental approach and that's what we have discussed with all flexibilities we are having. Now, with this, all these fundamentals, it is preferred that we will be solving some of the numerical, that's what will build confidence in you, in order to do the calculation at different stations.

So, in next lecture, we will try to opt for design approaches and then we will be discussing about what all need to be changed or what all will be the changes in the design. So, thank you, thank you very much for your kind attention! See you in the next class.