Aerodynamics Design of Axial Flow Compressors & Fans
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Lecture 18
Design Concepts (Contd.)

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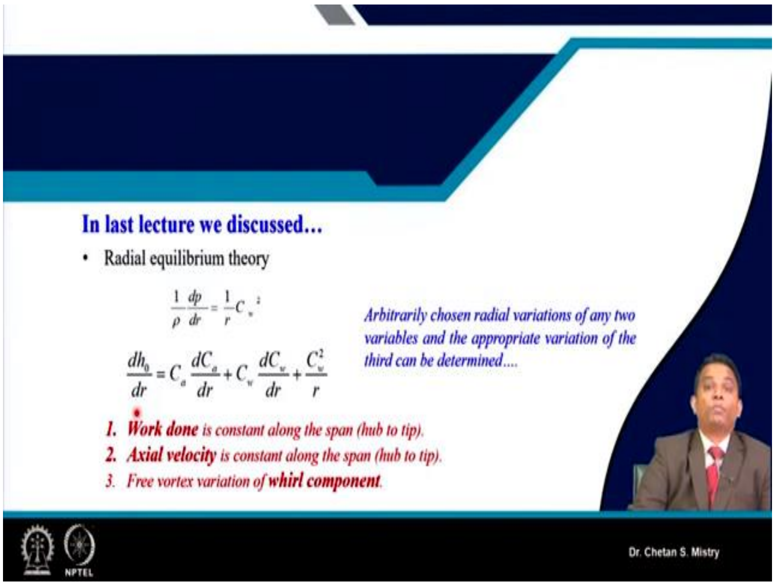

Hello, and welcome to lecture-18, module 3 for Design Concepts. So, in last lecture, we were discussing about very important aspect for say design of axial flow compressor or say, may be we can consider for design of any turbo machinery. We have come up with the equation that's what is called radial equilibrium equation. So, that radial equilibrium equation, that's what will be helping us in order to determine the variation of my pressure along my span. So, that's what is a function of my tangential velocity component.

So, we can say my $\frac{dp}{dr} = \frac{\rho}{r} C_w^2$, then based on our fundamental understanding of thermodynamics, we have come up with the formulation that is what it says my stagnation enthalpy change along my radius that's what is a function of my axial velocity and change in axial velocity, component of tangential velocity and tangential velocity variation along with my centripetal force.

$$\frac{dh_0}{dr} = C_a \frac{dC_a}{dr} + C_w \frac{dC_w}{dr} + \frac{C_w^2}{r}$$

Now, if we recall, we have done certain assumption. We assumed the work done to be constant along the span; we have assumed our h to be constant along my span, that's it is not varying from hub to tip. Second assumption what we have made, it is we are assuming our axial velocity to be constant. So, that's what is not varying along the span and based on these two assumptions and using this formula, we come up with the formulation, that's what is we have defined as a free vortex flow.

So, you can say, it says the variation of my work component that's what is following the rule, it is say free vortex rule. Now, you can understand based on our assumption what we have come up with that's what is very useful for our further movement. So, what it says? If we are considering arbitrary variation of two of the variables, suppose say my work done and my axial velocity, suppose if I consider my axial velocity and tangential velocity component.

Based on those assumptions, it will be possible for us to calculate the variation of our third component. So, that's what is the use of our vortex energy equation. So, now we will be discussing in detail how do we move forward with our detail understanding for further design aspects.

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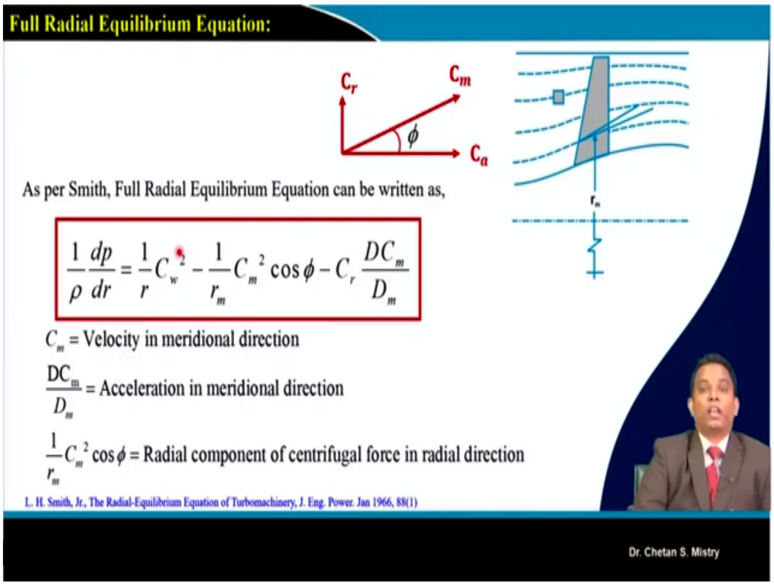

So, before going into detail, say… we have simplified our problem, we have derived with our radial equilibrium where we have not considering any variation of radial velocity component. Now, Smith in 66, he has written, he has given full radial equilibrium equation and according to him this is what has been represented in sense of my say $\frac{1}{\rho}\frac{dp}{dr}$ that's what is

$$\frac{1}{\rho}\frac{dp}{dr} = \frac{1}{r}\, C_w^2 - \frac{1}{r_m} C_m^2 \cos\phi - C_r \frac{DC_m}{D_m}$$

Now, let us try to understand what exactly is a meaning here? So, here if we look at, we have discussed because of my flow passage, because of change of my area, we will be having radial velocity that's what is coming into the picture and in order to simplify that case what they have done? Say… having say, this is what is my axial velocity component you can understand the magnitude and here we are having radial velocity component.

So, rather considering my axial flow as a velocity component for my fluid to move, they have considered this meridional velocity component. So, here this is what is ϕ, that's what is representing what will be the inclination of my flow and how my area change that's what is affecting the movement of my stream lines.

So, here if you look at, this C_m, as I told, it is a velocity in meridional direction, $\frac{DC_m}{D_m}$, that is nothing but its acceleration in meridional direction and this term $\frac{1}{r_m}C_m^2\cos\phi$, it is radial component of my centrifugal force in radial direction. So, if you are putting all together, that's what is giving us idea about how my flow three dimensionality that will be coming into the picture and how do we use our radial equilibrium theory.

Now, in order to simplify the problem, we are not considering this variation; but the present trend, say when we are designing our single stage, this variation it is not making much sense, but when we are analyzing all stages, suppose say HP compressor it is made up of 10 stages, so under that condition this calculation, that's what is must. Suppose say my LP compressor, it is made up of number of stages, there, this calculation, that's what is must.

So, people those who are working for the development of CFD codes, they people, they are considering this analysis for flow field analysis, okay. Here in this case they are considering how my change of radial velocity that's what will be coming into the picture. So, more trained, mostly for all engine manufacturing companies, they are having their own code for say simulation.

So, in line to that, people, many people in University level, they are also working on analyzing this flow. This is what is called streamline curvature method. We will not be discussing this into detail, but this is what will be giving us idea what is our full radial equilibrium equation.

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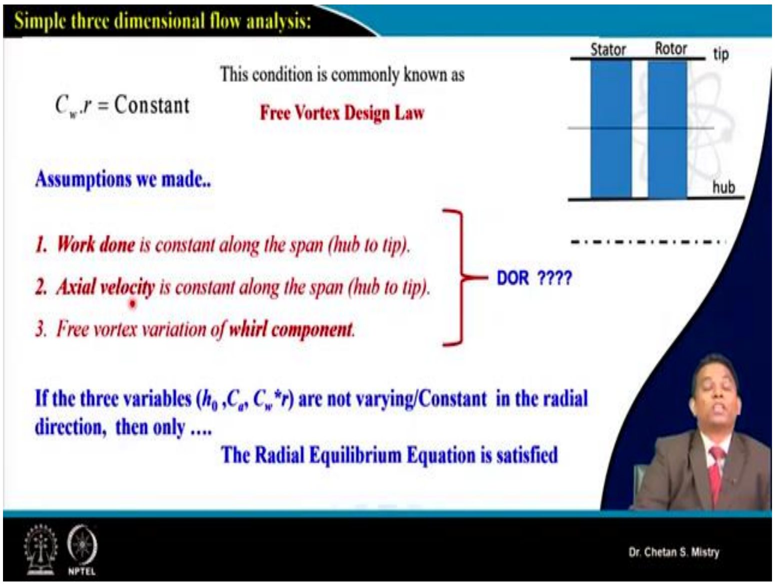

Now, here what we have analysed? Say we have come up with our equation, it says $C_w \cdot r = constant$ and we have defined that as a free vortex design. So, what all assumptions we have made? We have assumed our work done to be constant along my span, we have considered, say there is no variation of my stagnation enthalpy.

Then we have assumed our axial velocity that's what is not going to change along my span and based on these two, we have come up with the formulation for free vortex, that's what is says my vortex or say my whirl component that's what is varying in a systematic way; that's what is called $C_w \cdot r = constant$.

So, you can understand, if I consider my variables at say h_0, C_a, C_w; if they are not varying or remains constant in radial direction, then we can say then and then only my radial equilibrium is getting satisfied. So, basically in order to satisfy the radial equilibrium, these three condition must satisfy; that's what is the need, okay.

Now, along with this, we are more interested in our parameter, that parameter we are defining as a degree of reaction. Now, the situation is question always will come what is happening with our degree of reaction, if you are making this assumption, okay?

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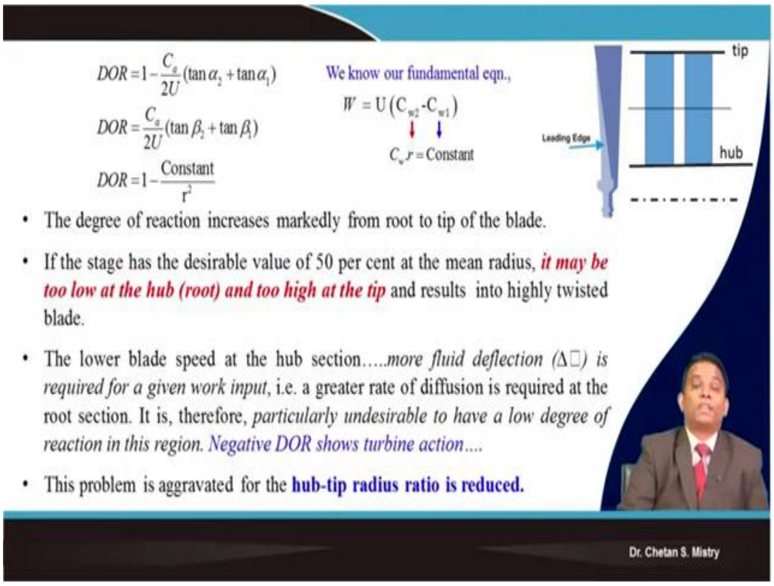

So, we can say, my degree of reaction, that's what is given in sense of α and in sense of my β. If I will be simplifying my equation, it says, my degree of reaction will be coming as say $DOR = 1 - \frac{constant}{r^2}$. Now, if we try to understand, what is the meaning of this equation? You can say, my degree of reaction, that's what is varying with my radius. So, you can say, it will be increased progressively from root to tip. We can understand, root is nothing but that's what is my hub and tip, we can say that's what is my casing.

So, you can say, you will be having great variation of degree of reaction all the way from hub to shroud. Now, we can say, if the stage has desirable value of 50% reaction, it may possible that near my hub, my degree of reaction that's what will be going to be reduced, okay. Because, we can understand my degree of reaction it is a function of my radius. It may be possible, because of that my angle, that will be coming to be large, that's what will be giving highly twisted blade.

So, you can see here, say this is what is my case; if you look at near the hub region, my $\Delta\beta$ that's what is coming to be large. And here near my tip region, my $\Delta\beta$ that's what is coming to be slightly lower. But we need to understand why this $\Delta\beta$, that's what is coming to be higher? We must realize, our peripheral speed, that's what is the function of my radius, okay. So, you can say, if I am considering my peripheral speed to be lower near the hub region, then I need to have great deflection of my flow near the hub region, okay.

And that’s what is in order to achieve high pressure rise or in order to do more work in that particular region, okay. So, that’s what is asking for more amount of diffusion in that region, it may be possible that you will be calculating your degree of reaction and that degree of reaction that may be coming to be lower. Sometimes, when you are doing your calculation, you will realize when we will be doing the actual design you will find degree of reaction is coming negative.

Now, we know, when I say degree of reaction to be 0 that means whole my diffusion, that’s what is happening only in my rotor, is it, okay? Now, the situation is, this is what is wrong; we say, my degree of reaction that’s what is coming to be 0 my whole diffusion that’s what is happening in my stator, okay.

Now, if I say my degree of reaction, that’s what is coming to be negative, that means in place of having diffusion to happen there I will be having the acceleration of flow. So, that particular region, rather acting like a diffuser, it will be acting like a nozzle and that’s what will lead to losses. So, that particular region, that will not be giving me pressure rise. So, that’s what is coming in sense of loss, okay.

So, we can say, I should avoid my degree of reaction to go 0 or maybe in a negative value. This problem, that’s what will get aggravated when you are having your hub to tip radius ratio, that’s what is say, reduce. So, we can understand, when we are having our hub radius, that’s what is coming to be lower, it is but obvious my peripheral speed is going to be lower, we will discuss this point again.

But at this moment, just try to understand our degree of reaction that’s what is varying from lower value at the hub and having higher value near the tip and that’s what is giving highly twisted blade. When I say highly twisted blade, that’s what is a problem with our design. When I say design problem, when we are giving those kind of blade for manufacturing, because of highly twisted blade, it will be more challenging to fabricate those blades, okay.

It is not that people they are not making or not doing design based on free vortex, yes as on today also people they have preferred to go with the design of free vortex, but as I told we need to be very careful in sense of setting our degree of reaction near the hub region, okay.

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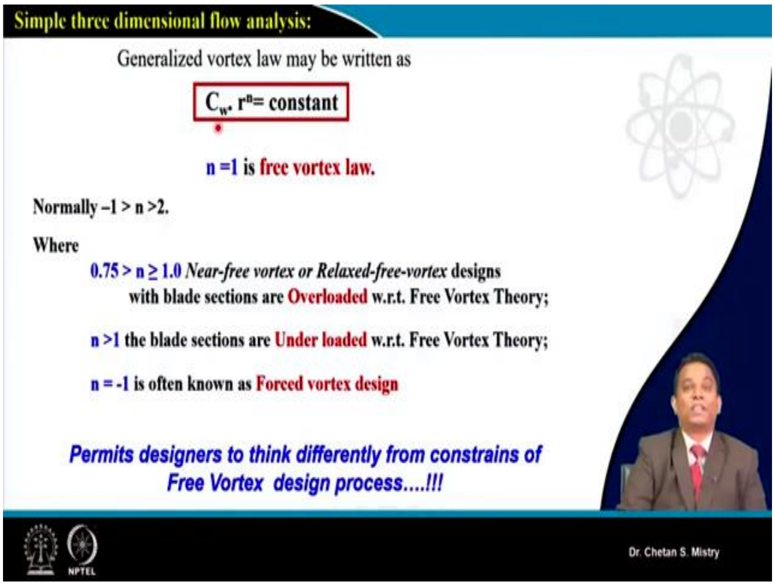

Now, say what we have discussed, that is what it says my free vortex formulation. So, let me rewrite the equation say it is more generalized vortex law; we can write down $C_w \cdot r^n = constant$. What I am doing? I am just replacing $r\ by\ r^n$, in that if I will be putting my $n = 1$, that's what is giving what we say as a free vortex design, okay.

Now, normally this n, that's what is varying between $-1\ to\ 2, okay$ Now, let us try to understand, what is the meaning of these numbers? So, here if you look at, when we are having our n, that's what is in between 0.75 to 1; we can say, this is what is defined as a relaxed free vortex design, okay. And, that's what will be giving the overloading of my blade with respect to free vortex design. We will see where exactly we are looking for such kind of configuration.

So, you can say, when I am changing my r to the power n, if I will be putting my n, that's what is creating say different kind of design aspects, okay. Now, if we are considering say my n, that's what is greater than 1, that's what is giving me under loaded design with respect to free vortex design, okay. And if I will be taking my $n = -1$, that's what is often, that's what is defined as a forced vortex design.

Now, we need to realize, you know, we are having limitation with our free vortex design. We have two limitations what we have discussed; one, that's what is having highly twisted blade and second, that's what is with the change of my degree of reaction, okay.

So, that's what is putting constraint to designer to design the blade. And, in order to get rid of that those limitations, people they have come up with say having say different approach and this is what is the approach what we are writing at this moment, that's what is $C_w \cdot r^n = constant$.

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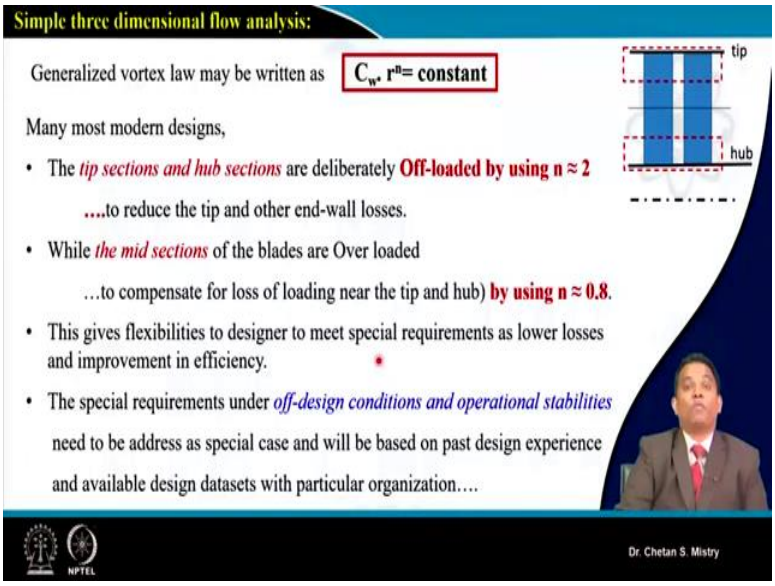

Now, suppose if we are considering this is what is my variation of whirl component, we must realize this is nothing but that's what is representing how my whirl component or tangential velocity component, it is varying along with my radius, okay. Do not misinterpret in other way, just try to understand here, say my $C_w \cdot r^n$ at particular station, that's what is constant, okay.

Suppose, say… this is what is my blade; at mid station, if I know what is my C_w, if I know what is my r^n, I can calculate that constant. Now, based on that if I am considering, if my design, that's what is say free vortex design, I can calculate how my C_w that's what is varying along my span, because I will be changing my value of r. So, we will see, what exactly and how exactly we will be doing the calculation for our free vortex part, okay.

Now, it says for most modern designs the tip section and hub section they are deliberately off-loaded by using $n = 2$, that is what we were discussing earlier. The reason is, this is what is in order to minimize the tip and the losses, that's what is related to end wall. So, near the hub region and near this tip region, we will be having the variation of n, that's what is $n = 2$, okay.

Now, at the mid-section, they are overloaded, that means in order to compensate for what losses in loading we are getting. Just understand, when I am taking $n = 2$, that means it is not that much loaded, okay. In order to compensate that loading or in order to achieve that loading, we are considering this $n = 0.8$ near the mid stations, okay. Now, this is what is giving us the flexibility in sense of selection of our design approach, okay.

And we are able to lower the losses and that's what will lead to increase in efficiency or the improvement in the efficiency of that particular stage. Now, there are other special requirements. So, you know, as we were discussing, we are not having only approach to improve the efficiency; we have other criteria, say…. we are looking for say improvement in overall operating range, we are looking for improvement in off design condition.

We are looking for the stability of my flow or we can say, we would like to enhance the operation of particular stage for compressor, okay. And for that case, for most of the organization, they are having their own design database and based on their understanding, based on their experience, based on their computational work, based on their experimental work, they people they have made their database and again and again when they are doing the design, that time they are using that approach.

Let me tell you, do not underestimate the design of say your axial flow compressor. It is not that we will be taking one compressor, one axial flow compressor stage from one engine to other engine and that will work. All these axial flow compressors need to be designed indigenously. So, all engines they are having their compressor design, that's what is indigenous design, let it be LP compressor, let it be HP compressor.

So, you can understand, that's what is running the whole industry for say gas turbines, okay. And when we are talking about the special application, for Aero engines, that will be more challenging, okay.

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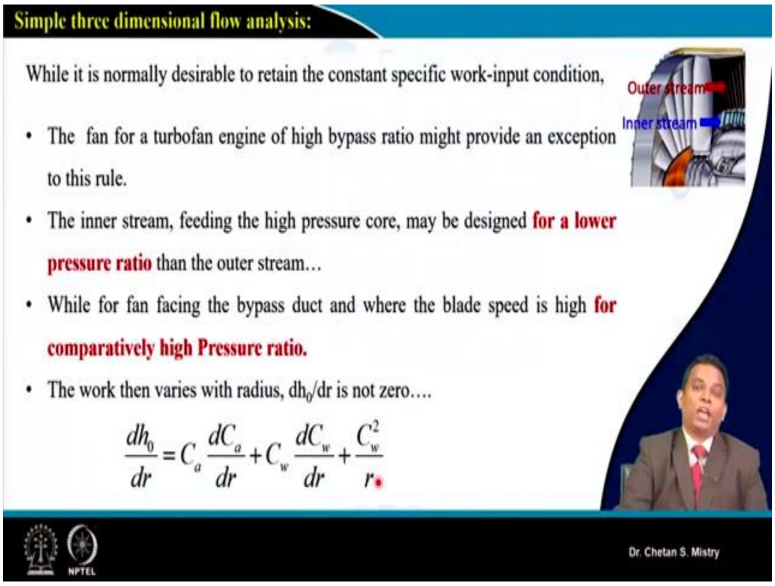

Now, let us move, suppose if you are considering say high bypass ratio design. Say, this is what is say my high bypass ratio fan. Now, you can understand, some amount of air that will be entering inside my LP stage here, so you can say, this is what is called inner stream and outside, that's what is called outer stream of my bypass ratio fan or say bypass fan, okay.

It says, if we are considering, then the law what we are talking about the design, that's what is say… my design using, say…. energy equation, vortex energy equation, that's what is not straight way applicable here with certain assumptions. What it says? My inner stream, that's what is giving the high, that's what is moving towards say high pressure core. So, this is what is called core engine, okay. And that is where the pressure ratio requirement, that's what is to be lower.

So, here, what air that's what is entering inside this core, that's what is entering at a low pressure. When we are considering on the upper stream, we are, if you look at, that's what is having say high pressure ratio. So, you can understand, when I say, my fan, it is having the pressure ratio of 1.6, 1.8, 2; that's what has been distributed along my span, okay. So, that is the reason why the design of these fans, they are always challenging, okay, not because of size; but, you can understand, the operation requirements are different.

So, under that condition, we need to consider, say… we can say, my $\frac{dh_0}{dr}$ that will not remain 0. So, you need to literally sit down and calculate $\frac{dh_0}{dr}$ based on change of my axial velocity, based on change of my tangential velocity component and based on my centripetal action, okay. So, this is what is giving you some of the idea in sense how do we approach with the design.

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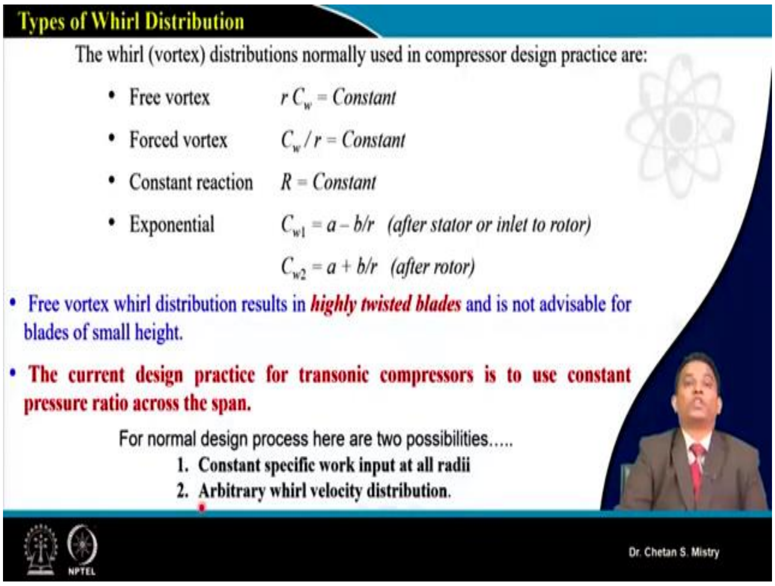

But still, let us try to move, in part we can say, we have discussed, when we are having our $C_w \cdot r^n = constant$, we have discussed different approaches. But, as on today, for our compressor design, people they are taking different design approaches, one of them as we have discussed is a free vortex design in which $r \cdot C_w = constant$, okay.

If we say, my $\frac{C_w}{r} = constant$, that is defined as a forced vortex concept. We can have constant reaction design, so, where we are considering our degree of reaction to be constant. There are approaches people they have come up with, that's what is called exponential design approach, where my whirl component after the stator and at the inlet of my rotor that is given by $C_{w1} = a - b/r$ and at the exit of my rotor, we can say $C_{w2} = a + b/r$.

Now, you can understand, how people they are thinking of changing this formulation. Now, they have come up with a different kind of approach for designing, we will be discussing this part. So, it says, for free vortex design, people they are saying, that's what is giving the highly twisted blade and that is the reason why it is not advisable when my blade height is small, okay. Because, that's what is giving highly three-dimensionality of my flow.

And it says, current design practice for transonic compressor, people they are taking the approach of constant pressure ratio across the span we have discussed. Say, when we are talking about the design of fan, that is where we are considering some other kind of approach, okay.

So, the normal design process, that's what will be having two different kind of possibilities; one possibility, we can say it is constant specific work input at all radius and second, that's what is say arbitrarily whirl velocity distribution, okay.

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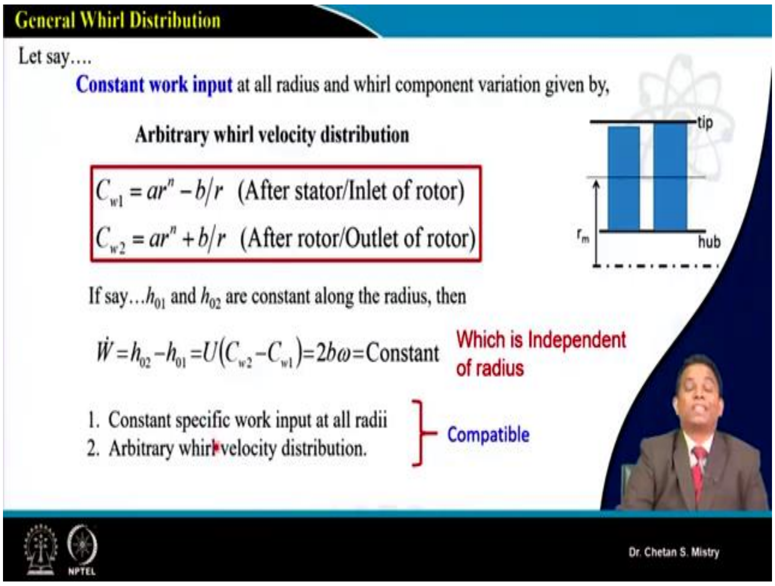

Let us have look at what exactly is a meaning here? Now, what we have realized? Let us say, if we consider, I am having constant work done or constant work input at all the radiuses and if we consider, my whirl component, that's what is varying with the radius and that's what is given by arbitrary whirl velocity distribution, okay.

This arbitrary whirl velocity distribution we are writing as say after stator or at the entry of my rotor, just do not get confused the meaning of after stator means suppose say I will be having first stage at the exit of my stator that will be the entry of my rotor for the next stage, that's what is given by

$$C_{w1} = ar^n - \frac{b}{r} (After\, stator/Inlet\, of\, rotor)$$

$$C_{w2} = ar^n + b/r\ (After\, rotor/Outlet\, of\, rotor)$$

Because, we are more interested, what is happening with the change of my tangential velocity. Remember one thing, the change of tangential velocity, that is what we are correlating with our work done and we are correlating that with my pressure rising capacity. So, again and again when we are talking about tangential velocity component do not get confused, what is the use of tangential velocity component, because this is what is a main parameter what we need to understand.

If we consider say my h_{01} and h_{02}, that's what is constant. Say… what we have assumed as say constant specific work input. If I will be putting that, so my W, that's what will be changing in the form of $2b\omega$. You can say, that's what is independent of my radius, okay. And that's what is we are assuming. What is our assumption?

We say, you know, my constant specific work at all radius and second assumption what we are discussing is say, arbitrary whirl velocity component. And these two equations, that is what seems to be 'compatible' in sense of moving further, okay.

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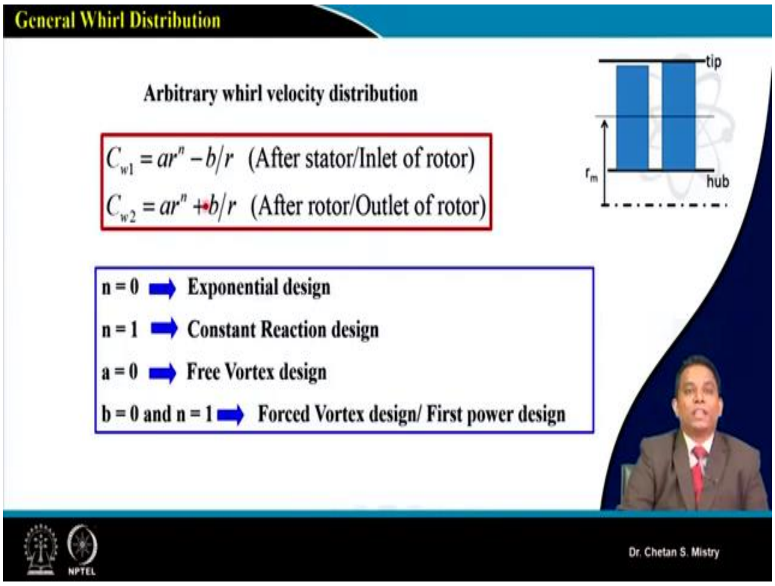

So, if we consider here, say this is what is say arbitrary whirl velocity distribution what we have and we can say, at the entry of my rotor, I will be having my C_{w1} and at the exit of my rotor, I will be having my C_{w2}. Now, we have correlated this C_{w1} and C_{w2} in the form of exponent n. So, if we are writing in this equation if I will be taking again, say my $n = 0$, that's what is giving me my exponential design, okay.

If I will be taking my $n = 1$, that's what is giving me constant reaction design and if I will be taking my $a = 0$, that's what is saying my free vortex design concept. And suppose if I consider, I am having my $b = 0$ and $n = 1$, that's what is giving me forced vortex design or say first power design.

So, we are more interested in considering arbitrary variation of whirl component, because we have realized, we will be simplifying our calculation by assuming the free vortex concept, but still we need to go with other approaches, too, in order to understand what is happening. Now, the question may arise in our mind what about this constants a and b?

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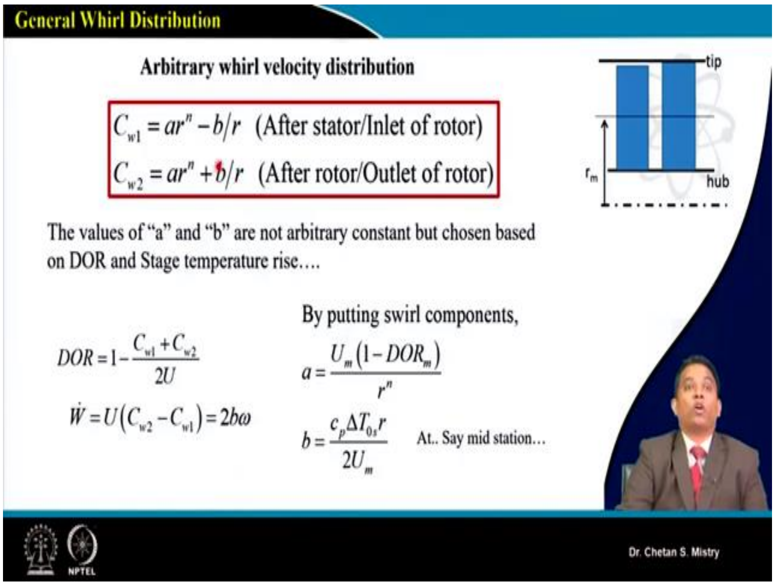

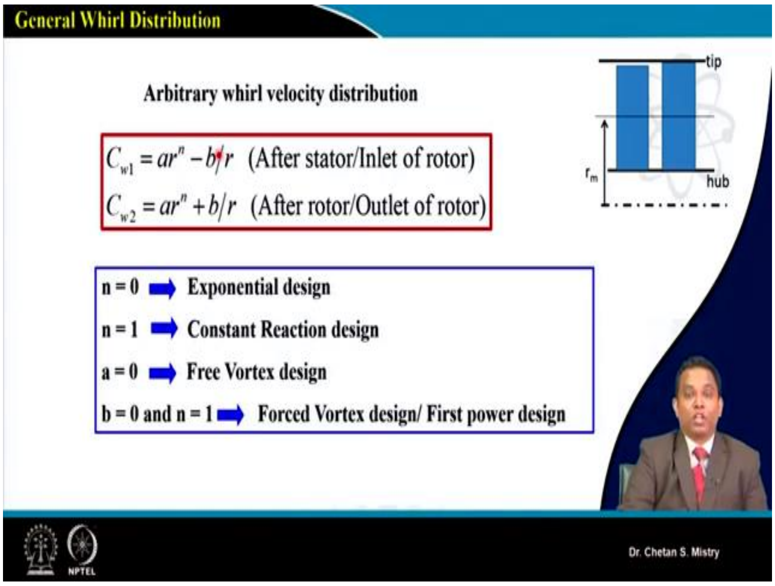

So, here if you look at, this C_W, as we have discussed, at the entry Cw1 and at the exit my Cw2; what we know from our fundamentals? This a and b that can be calculated based on our degree of reaction and what we can say my stage temperature rise, okay. So, here if you look at, this is what is representing my degree of reaction, that's what is

$$DOR = 1 - \frac{C_{w1} + C_{2w}}{2U}$$

and this work that is what we are representing $\dot{W} = U(C_{w2} - C_{w1})$ and that's what we have derived here $\dot{W} = 2b\omega$.

If you are simplifying this equation, you will be getting your a, constant a, that's what is in the form of my peripheral speed at the mid-section, my degree of reaction at the mid-section and this is what is varying with my radius, okay. Same way, my b, we can calculate based on my stage temperature rise and that's what is a function of my r.

So, you can understand, this constant a and b, they are also function of my radius, okay. So, we can calculate what is our value of a and b at the mid-section, such that it will be easy for us in order to understand or in order to calculate our arbitrary whirl velocity distribution at the entry as well as exit.

Now, what all we were discussing about, that's what is say my exponent $n = 0$, my $n = 1$, my constant $a = 0$, constant $b = 0$ and $n = 1$ configuration, that's what will be giving us some idea for say future designs. So, in next lecture, we will be discussing about how do we use this concept for further design of axial flow compressor. Thank you, thank you very much for your attention.