**Aerodynamic Design of Axial Flow Compressors & Fans**
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**Lecture – 9**
**Stage Configuration and parameters (Contd.)**

Hello, and welcome to lecture – 9 on NPTEL online certification course for Aerodynamic Design of Axial Flow Compressors and Fans.

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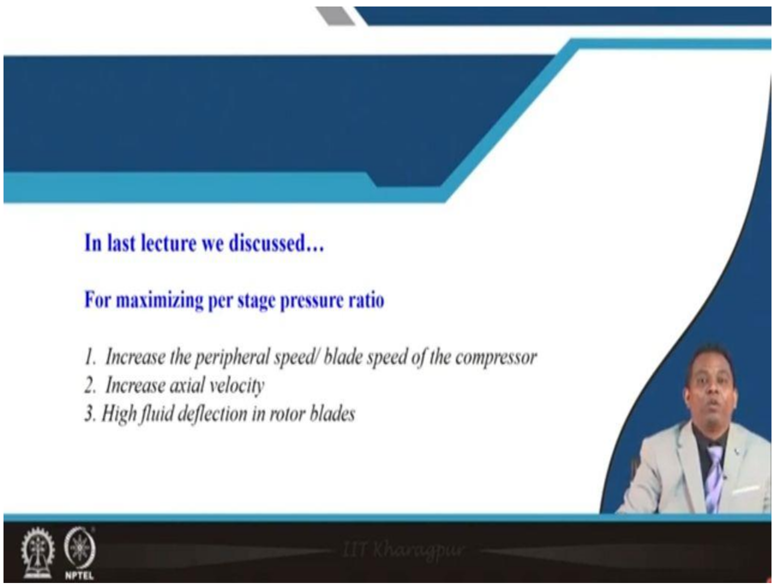


In last lecture, we were discussing about maximizing the per stage pressure ratio; that's what is a recent trend, this is what is a requirement from industries. Specially, these requirements are for aero engines where our size, our weight and our operability, that's what is of major concern. It says in order to increase your per stage pressure ratio; we need to increase our peripheral speed of the rotor. We need to increase our axial velocity; that's what is going inside my engine. We need to increase the blade deflection of rotor in order to achieve high pressure rise.

And for first two cases we have observed like with increase of peripheral speed or by increasing your axial speed or axial velocity; that's what is lead to have sock formation will be happening near the tip region, okay. And that will lead to increase your losses and blockage to your flow that will be reducing your efficiency.

Using your higher blade angle or higher blade deflection angle, that's what will lead to flow separation. Since we are working under adverse pressure gradient, we will be having the separation of flow that will be happening on my suction surface of the blade or maybe on the pressure surface of the blade.

Now, when we are having higher deflection angle for the rotor, and if you are looking for axial exit, my design for stator also will be very challenging. So, that is the reason why people they are finding different ways to address these issues. So, as we move ahead, we will be discussing what all development activities which are going on globally to address these issues. Now, let us move with the next case.

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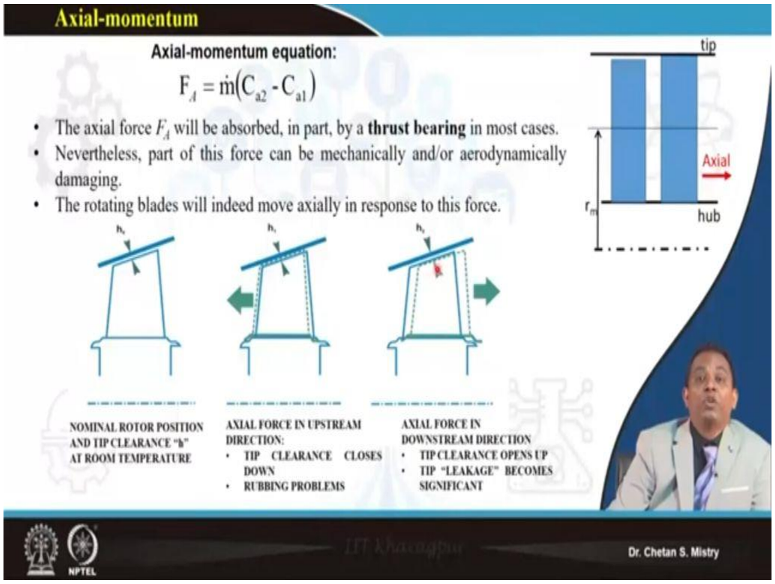


Say, we are putting a term, that's what is say our axial momentum. So, we have three major velocity component, rather fourth velocity component, we are correlating with our diffusion process. Suppose, if I consider I am having my axial velocity, so my axial-momentum equation, that will be written by $\dot{m}(C_{a2} - C_{a1})$, okay. So, this is what is nothing but that's what is representing my axial force component. And this axial flow component, that's what will be taken care by using your thrust bearing, okay. So, you know, this is what is responsible for your mechanical and aerodynamic damage to the rotors, okay.

So, you know, if we look at here, say for this case, we know we need to provide certain amount of clearance between casing and rotor in order to have free rotation of my rotor. We realize this is what is a mechanism where I will be having, say loss, that's what is happening; that's what is called tip leakage loss.

So, if I will be putting my gap between this rotor and casing to be say certain amount, it will give better pressure rise and better efficiency; because I am able to reduce my losses. Now, what happened? Because of some reason, suppose if I consider your axial force, that's what is acting in axial direction; so, you can see this is what is say my axial direction.

There may be possibility that my rotor will try to move in forward direction like this, it will be moving in upstream direction. So, what will happen? What clearance we have provided between casing and the rotor, that's what is going to reduce; and there maybe chances that my rotor will be touching to my casing. And that's what will be giving you catastrophic failure.

So, in past, many such failures, they are happened. Now, if I will be going in other ways, suppose if I consider, say my axial force is acting in, say, downstream direction. So, if this is what is your case, you can see, I will be having the gap between rotor and casing that's what is going to increase. If this is what is your case, you will be having the tip leakage flow contribution to be increased. That's what will be lead to reduce in pressurizing capacity of the rotor as well as it will be reducing your efficiency, okay. So, we need to take care of what we say, that is nothing but the change in our axial velocity, because that's what is responsible for your axial say momentum.

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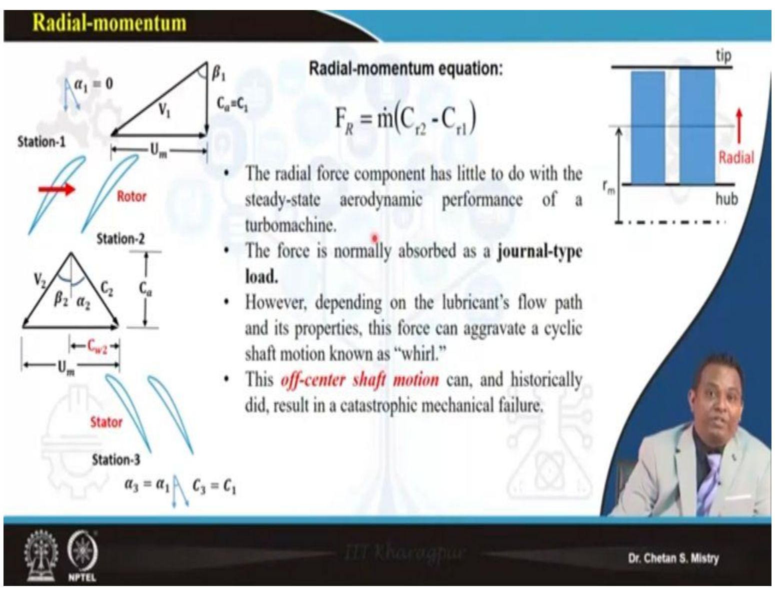

Now, next, we are having more component, that's what is say my radial component. So, this is what is representing my radial direction. So, what it says? My radial momentum that's what is given by $\dot{m}(C_{r2} - C_{r1})$, okay. This radial force, that's what has nothing to do with your steady state aerodynamics of the compressor. And mainly my journal kind of bearing that' what will be taking care of this situation. But, you know, depending on the lubricant flow and its property, the force can aggregate the cyclic shaft motion that's what is known as whirl, okay.

So, what will happen? My rotor or my shaft that will be rotating off-center. If this is what is your case, you will be having catastrophic failure of your rotor. So, there are mechanical failures which are happening because of change of this velocity components. So, we are not discussing anything in sense of mechanical aspect. But, you know, change of your velocity components that's what will be bringing you the change in your structure. So, change in your flow mechanism, change in your operation, okay.

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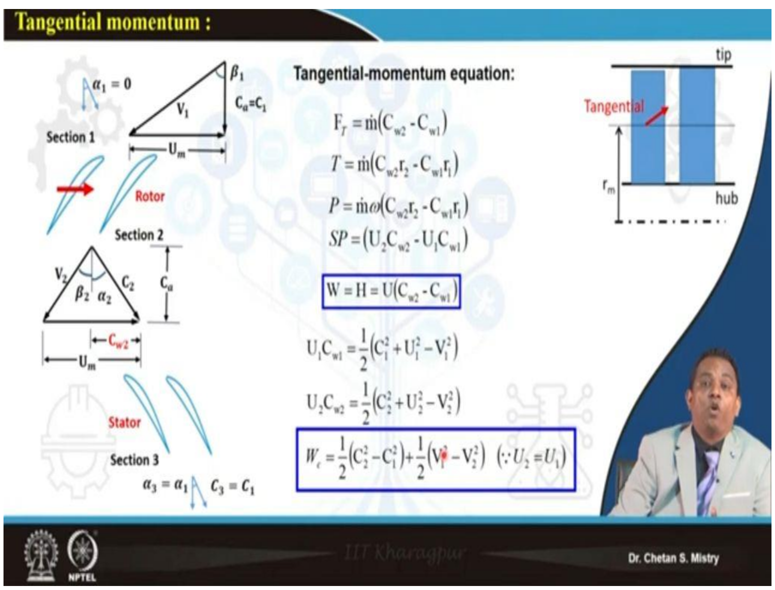


One more component what we have discussed, that' what is our tangential velocity component. So, that's what is responsible for my tangential momentum. So, my tangential momentum, I can say, that's what is written by $\dot{m}(C_{w2} - C_{w1})$. What I know, this tangential velocity component, that's what is responsible for generation of my torque. So, that's what I am writing here, in sense of my force into distance, that's what will give me a power as a equation; so, you can say my specific power, that is what we have already discussed $U_2C_{w2} - U_1C_{w1}$. And if I will be correlating using my cosine relation, we have derived with my work done equation to be one half say $\frac{1}{2}(C_2^2 - C_1^2) + \frac{1}{2}(V_1^2 - V_2^2)$; this is what all we have discussed.

So, now you can understand, we are having mainly three momentums that's what is happening because of your change of component of velocity, okay. And we need to be very careful in sense of doing design; we need to take care of doing our mechanical design, as well as when we are doing our aerodynamic design. Now, this is what will give you overall idea in sense of what all will be the use of our velocity components. Now, let us move towards the next.

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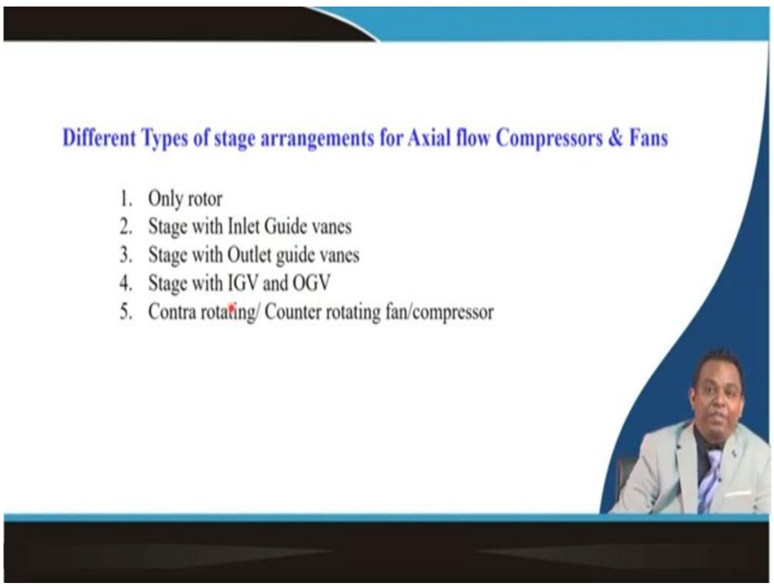


So, we are more interested in different kind of configurations, stage configurations, what we say. That's what is applicable to your fans as well as compressor. What all are the different configuration? It says we can go with only rotor configuration; we can use stage with inlet guide vanes, we can use stage with outlet guide vanes, we will be having combination of inlet guide vanes, rotor and outlet guide vane.

And we also can have contra rotating kind of configuration in which my rotors will be rotating in opposite direction. So, let us try to understand what all are the application of such arrangements, okay. So, we have discussed, we are discussing at this moment for design of say axial flow compressors and fans which have different applications, okay. So, let us try to understand what all will be the use of this fundamentals for your application. Now, let me move towards say next slide.

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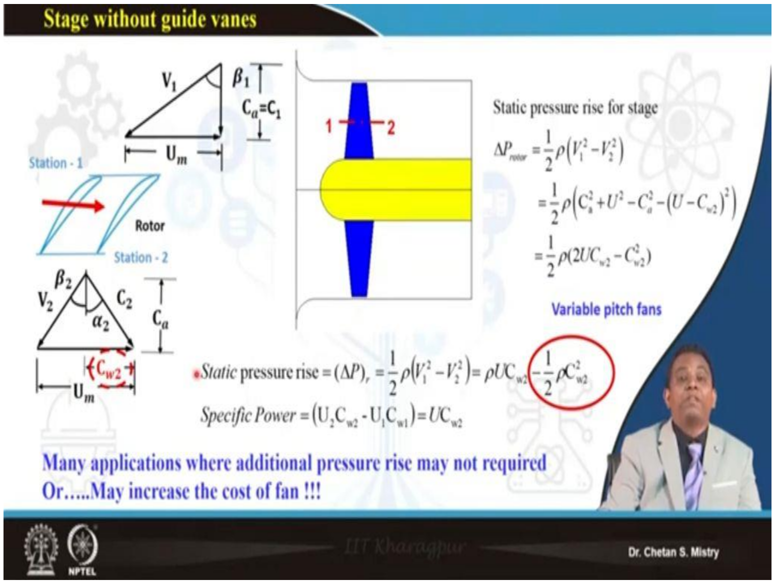


Say, this is what is I am having stage without guide vanes; I say I am having only rotor. So, here if you look at, this is what is representing my rotor, okay. Now, there are many applications where you have found there are only rotors, suppose if I consider the cooling fan, if I look at say my exhaust fan, my cooling tower fan, my wind tunnel fan. If you look at they are having this kind of configuration in which we are having only rotor. Even for high bypass ratio engine also, we are having big sized fan, okay.

But, realize one thing, fans what we are defining that has a different definition for aero engine that has different definition for our application part, okay. Now, here if I consider this is what is say my station 1 and 2, it is at the entry and exit, I can put by section with this airfoil. And if I will be drawing my velocity triangle let me consider for this fan, my flow is entering axially. So, I say my absolute velocity, my axial velocity, that's what is same. I know this is what is my peripheral speed at the midsection and this is what all we have discussed is representing my relative velocity component, and my blade angle at the entry or airflow angle at the entry.

Now, my flow that will be coming out with relative velocity $V_2$, okay, and I will be having my peripheral speed. And if I will be connecting, that's what is representing my absolute velocity component. Now, we assume our axial velocity is same upstream and downstream of my rotor. So, that is the reason my $C_a$, I am assuming to be constant. Now, this is what is my $\beta_2$ that's what is my blade angle at the exit. This is $\alpha_2$ that's what is my absolute flow angle. And you can see I am having my whirl component is $C_{w2}$.

Now, here we are representing our static pressure rise. When I say static pressure rise in my rotor, as we have discussed, my relative velocity component, that's what is responsible for generation of my pressure rise. So, that is what we are writing as $\frac{1}{2}\rho(V_1^2 - V_2^2)$. Now, this $V_1$ I can represent from this velocity triangle using my Pythagoras, I can write down $C_a^2 + U^2$, minus this $V_2$ we can represent in senses of this equation. Now, if once I will be simplifying this equation, it says my static pressure rise in rotor, that's what is given by this equation.

$$\Delta P_{rotor} = \frac{1}{2}\rho(V_1^2 - V_2^2)$$
$$= \frac{1}{2}\rho(C_a^2 + U^2 - C_a^2 - (U - C_{w2})^2)$$
$$= \frac{1}{2}\rho(2UC_{w2} - C_{w2}^2)$$

So, let me put this say static pressure rise that's what is say $\rho UC_{w2} - \frac{1}{2}\rho C_{w2}^2$. And my specific power or the power required for running of this fan is given by $UC_{w2}$. Now, if you look at carefully my static pressure rise what I am expecting, this is what is coming a negative term. What do you mean by this? It says my static pressure rise, that is what will be decreasing because of increase of my $C_{w2}$, or because of presence of my whirl component at the exit of my rotor, okay.

So, this is what is a component is responsible for my static pressure rise to be lower; but, at the same time my specific power, so, you can understand my specific power requirements since my pressure rise requirement, that's what is say lower, my power requirement also will be going lower. So, you know, there are many industrial application where additional pressure rise may not be required, okay. You are not looking for pressure rise, okay; and it says it may increase the cost of your fan. Now, just look at suppose say you are having your exhaust fan, that exhaust fan it is made up of only rotor, okay.

Now, when I say it is made up of only rotor, there is a meaning, there is a reason; or the whole purpose is only to supply the mass flow rate, to supply the air. My pressure rise is not coming into the picture; it may be having pressure rise, but it is lower. Suppose, if I consider the application say for wind tunnel. So, for wind tunnel, the whole purpose of providing the fan it is let my flow to flow through the test section, okay. And fan will be overriding what all frictional losses is happening in our wind tunnel, okay.

So, you can say my velocity requirement, that's what is say higher or my mass flow requirement it is higher. And it need to address the pressure drop that's what is happening within the circuit. Same if you are looking at say for cooling tower, you will be having pressure rise of few Pascal, okay. So, there we are not having, we are only having this rotor kind of configuration. These days people they are working on say other configuration; that's what is called variable pitch fan. So, this variable pitch fan it is not a new concept, people they already have explored. So, many times in order to change the flow through wind tunnel, we use to change the angle of our blade, such that we can increase or decrease the speed through the test section, okay.

So, many times people they are using mechanical devices in order to use variable pitch kind of configuration. So basically, variable pitch in the sense we are managing our $C_{w2}$ realize that thing. When I am changing my angle, say for this blade if I am changing my angle, it says basically I am managing my $C_{w2}$.

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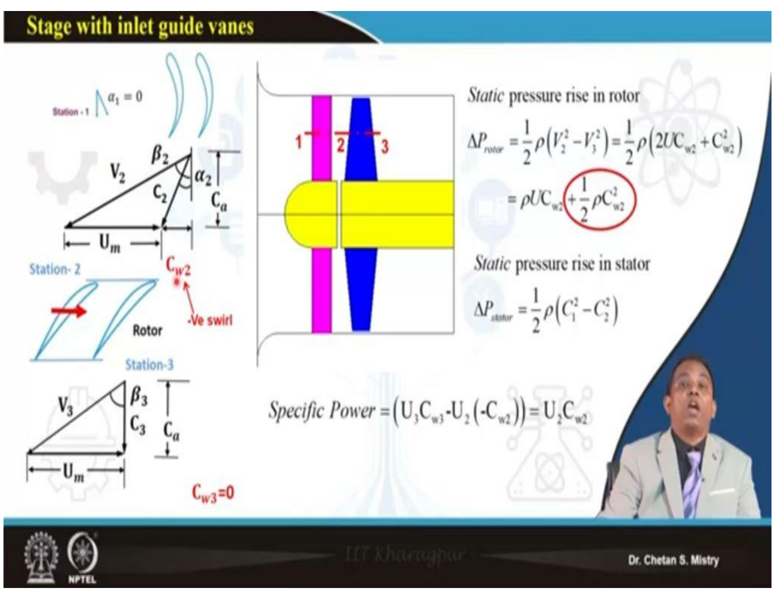


Now, let us move. Suppose if I consider, I am looking for reducing, or say I do not want my whirl component to be coming out from my rotor. So, that's what it says my $C_{w3}$, that's what is equal to zero. In order to achieve that what we need to do? We will be putting one stator or inlet guide vane here, okay. So, this inlet guide vane if I am looking at, I will be having my flow that is what will be entering inside my rotor at some angle $\alpha_2$ with some absolute velocity $C_2$. I know what is my peripheral speed, I will be getting what is my relative velocity component, okay. So, this is what is my $\beta_2$, the angle at which my flow is entering inside the rotor.

When it is coming out, okay, it will be having say my relative velocity component $V_3$, I will be having my U component. And just look at my exit will be axial one; that means my $C_3$ and $C_a$ they both are equal. Now, what is happening?

You know what we were discussing about the whirl component, that is what was coming out from the rotor when I am using only rotor; that is what we have addressed by incorporating this inlet guide vane. And here if you look at, I am having my whirl component, this whirl component that is nothing but, you know, if I will be writing my equation for my static pressure rise, it says this is what is getting added up; it is $\frac{1}{2}\rho C_{w2}^2$.

Now, the reason is, this is what is a negative swirl we are providing by incorporating inlet guide vane, okay. So, this is also one kind of configuration that's what is possible, in which my rotor that will be having say upstream inlet guide vane. If this is what is your case, your specific work or specific power requirement, that is what will be given by $U_2C_{w2}$, okay. Now, we will be discussing in detail about the inlet guide vane application for the engines.

Let me tell you, there are many applications. Suppose, say we are discussing about the mining fans. Now, in mining fans, they would like to exit the flow in axial direction; because this flow, that's what will be connected with your ducts. So, under that configuration, we are having this inlet guide vane that will be followed by the rotor. Many times in order to modulate the mass flow rate entering inside the rotor that also is done by using this inlet guide vanes, okay.

Rather, you can understand, say if I am using say variable pitch configuration for the rotor, maybe during a rotation condition, it will be a little tricky and challenging in sense of mechanical design, okay. So, when we say it is a mechanical design, then in a rotating configuration, change of this pitch it is very challenging. So, that can be modulated by using this inlet guide vane. That is what will be having say, you have modulation for your mass flow rate, okay. So, basically, what whirl component we were getting at the exit; that's what we have managed by incorporating the inlet guide vane.

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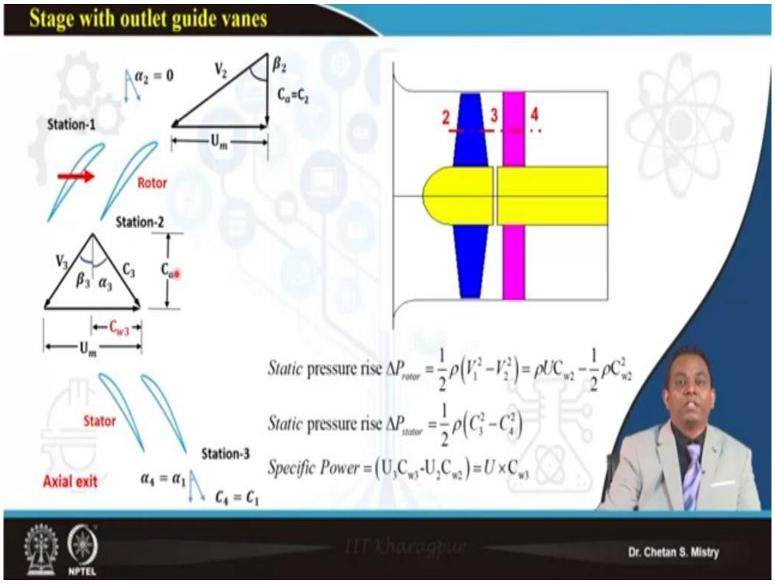


Now you will say, sir, why do not we try by providing the exit or say outlet guide vanes; so, this is what is a configuration in which we are having outlet guide vane. So, let me take at say mid section, we are having different stations. And for these stations, if I will be writing, I will be having this kind of velocity triangle. Here in this case, what we are finding? Here also we are having our exit to be axial one; so, you can see this is what is my axial exit, okay. So, by providing this outlet guide vane, basically we are taking care of our whirl component that is coming out from the rotor, okay.

So, if I will be writing my pressure rise, that is what will be coming to be slightly lower compared to our earlier configuration, okay. And my specific power, that is what will be the function of $UC_{w3}$, okay. So, what is my requirement, accordingly I need to design the configuration.

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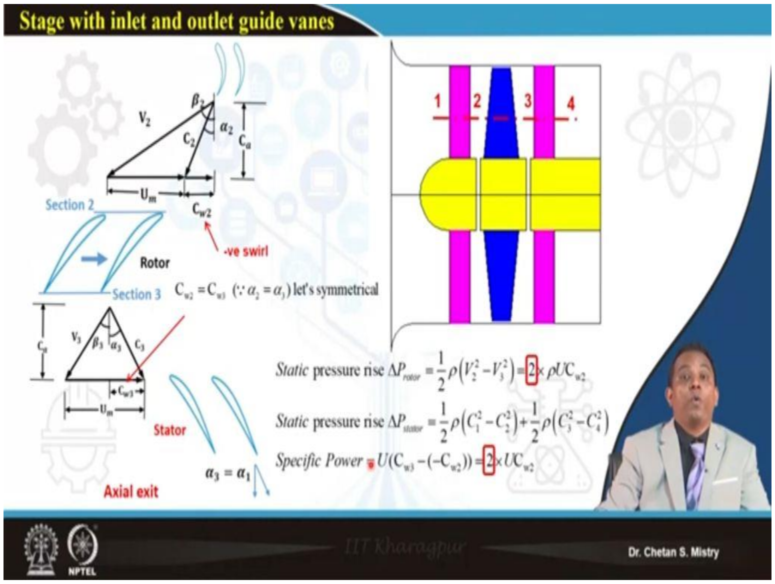


Now, with this you will say, sir, why do not we try with inlet guide vane and outlet guide vane both; and I will be having my rotor in between. So, it is like a multistage configuration kind of situation. People they used to say this as say one-half stage compressor, okay. If this is what is your case, you can say my flow that will be entering with some absolute velocity, okay, with some angle $\alpha_2$; I will be having my peripheral speed. If I will be putting, this what is my relative velocity component; I will be having my blade angle.

Same way, if I will be looking here, this is what it says my whirl component I am imparting by using inlet guide vane. So, at the entry of rotor, we are imparting our whirl component. Now, this is what it says negative whirl component, because that's what we have realized if we are using inlet guide vane. Careful! based on what kind of inlet guide vane you are putting, your whirl component will come. Here, for this kind of configuration, it is coming negative whirl; it maybe possible that you will be having your inlet guide vane that will give flow with positive whirl also, okay.

So, do not get confused with this part. Now, in sense of exit, this is what we have realized; we will be having my exit whirl component that's what is say my $C_{w3}$. Now, what do we want to do? We are looking for our axial exit. So, if we are looking for axial exit, we will be having stator vane that will be placed here, okay. Now, when we are doing this kind of design, we are assuming say symmetrical kind of configuration, and it says my $C_{w2}$ and $C_{w3}$ to be same. What it says, my $\alpha_2$ and $\alpha_3$ that is what we are assuming to be same.

If this is what is your case, you will find, you know, like my static pressure rise for the rotor, that is what will be double, okay. At the same time, my specific power requirement that also will be double, okay. So, kind of application what you are looking for, accordingly you need to decide with the different configuration for your rotor and stator, okay.

$$\Delta P = \frac{1}{2}(V_2^2 - V_3^2) = 2 \times \rho U\, C_{w2}$$

$$\Delta P_{stator} = \frac{1}{2}\rho(C_1^2 - C_2^2) + \frac{1}{2}\rho(C_3^2 - C_4^2)$$

$$Specific\ Power = U\big(C_{w3} - (-C_{w2})\big) = 2 \times UC_{w2}$$

So, we have seen we are having say only rotor kind of configuration; we are having rotor that will be, you know, having inlet guide vane. So, stage we can say inlet guide vane and rotor; we also can have rotor and stator configuration. We can have inlet guide vane, rotor and stator configuration.

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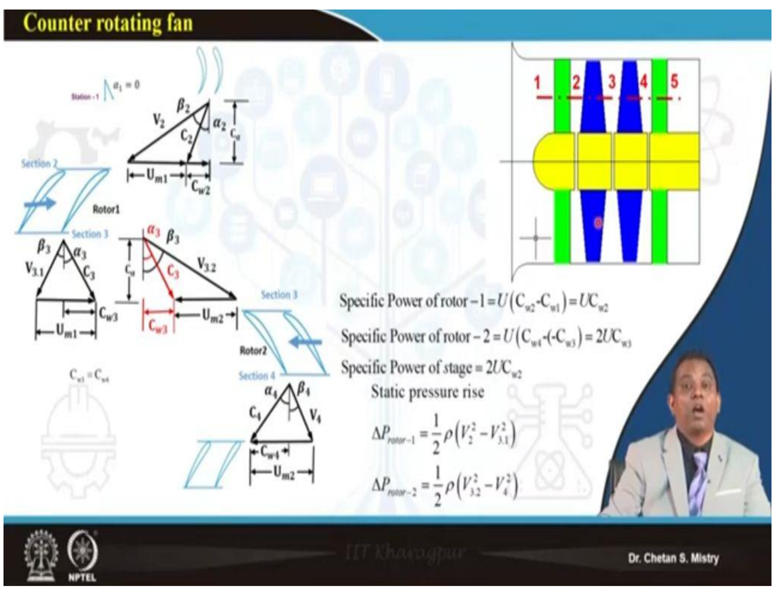


Now, let us discuss with some other approach, okay. Here if you look at, this is what is representing the contra rotating configuration. So, this rotor, suppose say first rotor, that's what is rotating in say your clockwise direction, then my rotor-2 that will be rotating in opposite direction; it will be rotating in counterclockwise direction, okay. So, this is what is very interesting case when we are discussing about different configurations. So, here if you look at, say this is what we can say as inlet guide vane and outlet guide vane.

There are many configurations in which we are not having say inlet guide vane and outlet guide vane in combination with contra rotating fan. This kind of starts is provided only for the support. But let say suppose if I consider I am looking for my flow to enter at certain angle, okay. So, this is what is my angle with which flow is entering, say it is my $C_2$. This is what is my peripheral speed of rotor-1. And if I will be connecting that's what is representing my relative velocity component.

So, this is what is known to you. Now, you are fundamentally clear how your velocity triangle at the entry that will be happening. In line to that if you are looking at we will be having exit with relative velocity $V_{3.1}$; purposefully, I am writing here 3.1. This is what is my peripheral speed, I will be having my absolute velocity $C_3$. And these are my angles, relative flow angle; we are having absolute flow angle, and my axial velocity, that's what is coming to be same. Now, this is what is my exit velocity triangle from rotor-1.

Now, what we know, say this rotor, that's what is rotating in one direction, I am having my second rotor, that's what is rotating in opposite direction. So, what happens? Let us see. Suppose, here I am making assumption, say my velocity, my absolute velocity, that's what is coming out from my rotor, that is what will be entering at the same angle to my rotor-2, okay. So, if I am putting my peripheral speed here, you can see this is what is making a kind of velocity triangle like this. And if we look at my relative velocity at the entry of my rotor-2, that's what is coming to be $V_{3.2}$. You can see that's what is larger compared to your entry condition for rotor-1 and exit condition of rotor-1, okay.

And this is what is because of, you know, what whirl component, that's what is coming out from my rotor that will be getting added up. You just try to understand here this is what is representing my positive sign and this is what is representing my whirl component in opposite direction. So, what basically is happening? Just look at if I am writing my specific power of rotor-1, it says $U(C_{w2} - C_{w1})$. And here if I am writing for my rotor-2, that's what is given by U $C_{w4}$, that's what is nothing but by exit configuration here, -(-Cw3) $[i.e. U(C_{w4} - (-C_{w3}))]$ , okay. So, here you can see you will be having your specific power for rotor-2 to be coming large, okay.

And if we are talking about the static pressure rise for both the rotors; that's what is given in sense of my relative velocity component. For rotor-1, it is $V_2$ and $V_{3.1}$. For rotor-2, that's what is $V_{3.2}$ and $V_4$.

$$\Delta P_{rotor-1} = \frac{1}{2}\rho(V_2^2 - V_{3.1}^2)$$

$$\Delta P_{rotor-2} = \frac{1}{2}\rho(V_{3.2}^2 - V_4^2)$$

So, by incorporating this contra rotating configuration, we are able to achieve high pressure rise. Now, let me tell you there are many advantages of this contra rotating configuration, okay. You can understand, suppose if I am removing my inlet guide vane, and outlet guide vane, it says there is no need of stator in between two rotors.

So, if I am eliminating my stator between two rotors, that's what will be reducing the length of my engine, okay. It will be reducing the weight of my engine if I am talking about application for say engines that is application for aero engines, okay. So, what it will be doing? It is reducing the length of my engine; it is reducing the weight of my engine, that's what is improving the fuel economy. Now, let me tell you, say for recent fighter, that's what is fifth generation aircraft F35. They are having engine that is F135 made by Pratt and Whitney in which all the compressors stages what they have designed, they all are of contra rotating configuration.

So, the concept of contra rotating is, you know, it is applicable for your compressor; it is applicable for your fan, it is applicable for your turbines, it is applicable for your propellers, it is applicable for your turbine. And whole fundamental for all this application, it is to deal with this whirl component, okay. So, what is happening my whirl component, that's what is coming out from my rotor; we are not managing for all current configuration. Let it be rotor, say inlet guide vane and rotor configuration; say rotor and say stator configuration; inlet guide vane, rotor, and outlet guide vane configuration.

For all these, we are basically trying to do something in sense of avoiding this $C_{w2}$ or whirl component coming from the rotor. And for contra rotating configuration, we are utilizing this thing, okay. Now, let me tell you for these rotors, it maybe possible that my rotor will be rotating at different speed, yes. So, you can have two spool configuration in which one of the rotor will be rotating with the help of low pressure turbine; one spool that will be rotating with the high spool configuration. That means it will be rotated by high pressure turbine. We will be discussing the design for this in the session. So, we have special week in which we will be discussing design of this contra rotating configuration; that's what is most upcoming technology, okay.

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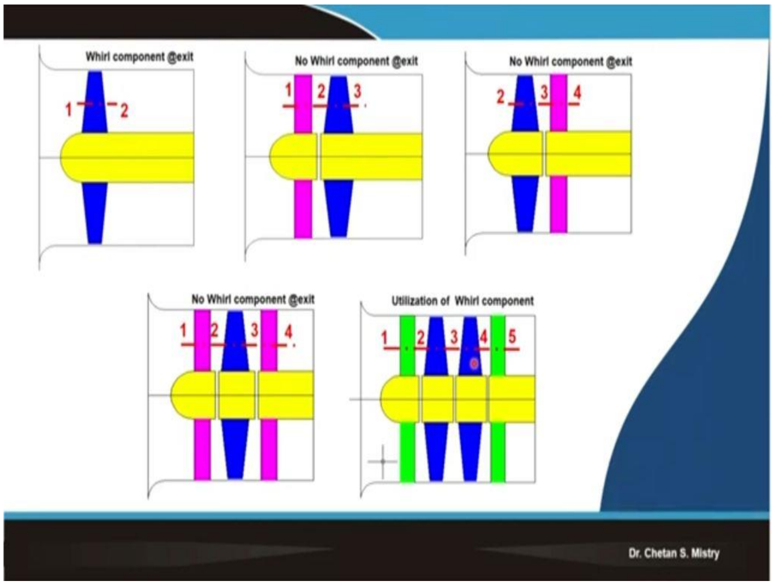


Now, in overall if we try to look at, say what all we have discussed today, that's what is in sense of only rotor configuration; say inlet guide vanes and my rotor configuration; my rotor and say outlet guide vane configuration or say stator configuration; we have inlet guide vane, rotor and outlet guide vane configuration, we are having contra rotating configuration. Now, what all we learned today is you know, my whirl component that's what is coming from my exit; that is what we are considering as you know, one of the problem, okay, and that is what.

But, you know, based on your application where you are using this fan, that's what is very important, okay. So, you are not bothering of having high pressure ratio or high pressure rise; there do not bother of this whirl component. If we go with the next configuration, what it say? We have tried to avoid our whirl component; that's what is coming out from my rotor exit. We found our exit to be axial one. So, basically, we have not utilized the whirl component in sense what it needs to be used for. We have, say you know, we have nullified the effect of whirl component, if I am talking about this configuration in which rotor that will be followed by my stator.

That is also having same kind of configuration; we have not done any implementation or use of whirl component, okay. Now, even for the configuration of inlet guide vane, rotor and outlet guide vane configuration, we are not taking any benefit of whirl component. But, we have realized the benefit of what whirl component; that is what will be coming out from my rotor-1. And that is what will be utilized in order to have my flow to be entering at my rotor-2, which is rotating in counterclockwise direction or in contra rotating configuration.

So, now being an engineer, we need to understand like how we will be using this kind of configuration. Suppose, say you will be working for a company where people they are no need to rise the pressure, okay. Suppose, say you are making cooling fans for say your computer or maybe for your processors. Under that configuration we are not bothering our flow direction. We are only interested in cooling purpose, where mass flow rate is of major concern; then, you need to go only with the rotor configuration.

When we are looking for special requirement for axial exit, we will be having configurations like what all we have discussed. And this contra rotating, that's what is giving you whole lot of benefits, you know, like we will be discussing in detail when we will be going for the design of this contra rotating fan. So, I am sure, this is what is giving you new kind of feeling.

How we need to understand different kind of configuration for the design of axial flow fan or axial flow compressor. Let it be having application for say your commercial for industrial purpose, let it be having application for aero engine, let it be having application for say your land-based power plants. So, here we are stopping with; thank you. Thank you very much for your attention!