Aerodynamic Design of Axial Flow Compressors & Fans
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Lecture 15
Stage Configurations and Parameters (Contd.)

Hello, and welcome to lecture-15 for Aerodynamic Design of Axial Flow Compressors and Fans. So, in last session, we were doing our tutorial and there was an assignment which was given to you, let us start with the solution for that assignment and then we will move ahead with.

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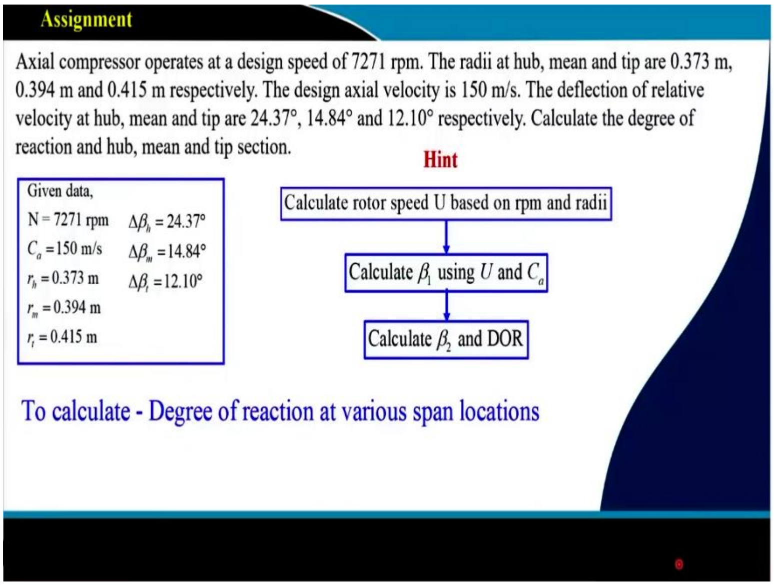

So, for assignment it was given, axial flow compressor operates at design speed of 7271 rpm, the radius at hub, mean and tip section are 0.373 m, 0.394 m and 0.415 m, respectively. The design axial speed is 150 m/s, the deflection at hub, mean and tip section that is given 24.37°, 14.84° and 12.10°, respectively, you need to calculate the degree of reaction at hub, mean and tip station.

So, as we have discussed, I have given you hint for the calculation of degree of reaction at different stations. We need to calculate our peripheral speed at different stations, axial velocity is known to us, angle β_1 that is what we can calculate based on our axial velocity and peripheral speed, the blade deflection angle that's what is $\Delta\beta$ is given, that will help us in for calculation of angle β_2 and based on that by applying your equation for degree of reaction we can calculate degree of reaction.

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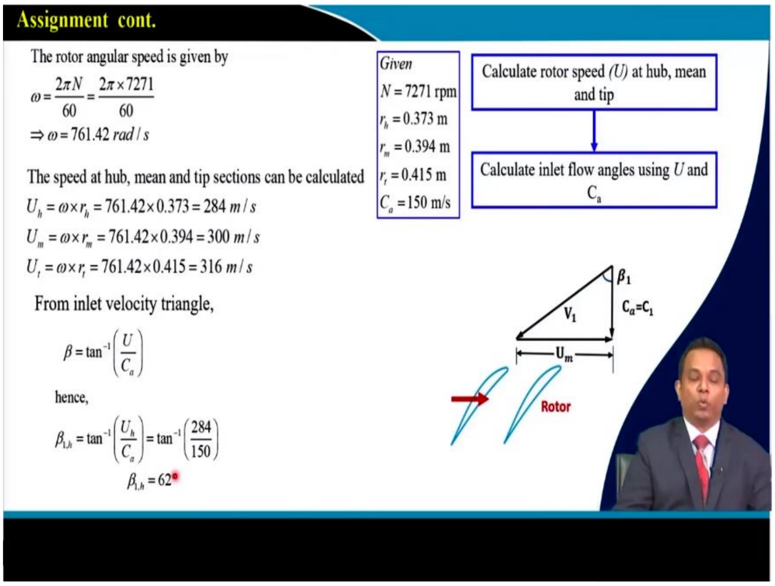

So, let us look at the solution. So, the angular speed that is given by

$$\omega = \frac{2\pi N}{60}$$

If I will be putting my speed as 7271 that's what will be giving me my angular speed as $761.42 rad/s$.

$$\omega = \frac{2 \times \pi \times 7271}{60}$$
$$\therefore \omega = 761.42\ rad/s$$

Now, at different station hub, mean and tip station, we can calculate our peripheral speed. So, this is what is giving me my peripheral speed at the hub as 284 m/s, at midsection 300 m/s and at the tip section as 316 m/s.

$$U_h = \omega \times r_h = 761.42 \times 0.373 = 284\ m/s$$
$$U_m = \omega \times r_m = 761.42 \times 0.394 = 300\ m/s$$
$$U_t = \omega \times r_t = 761.42 \times 0.415 = 316\ m/s$$

Now, based on our velocity triangle, we can calculate what will be my angle β_1. So, at hub station you can calculate that as say,

$$\beta = \tan^{-1}\left(\frac{U}{C_a}\right)$$

That's what is giving me my β_1 angle at the hub as 62°.

$$hence, \beta_{1,h} = \tan^{-1}\left(\frac{U_h}{C_a}\right) = \tan^{-1}\left(\frac{284}{150}\right)$$

$$\therefore \beta_{1,h} = 62°$$

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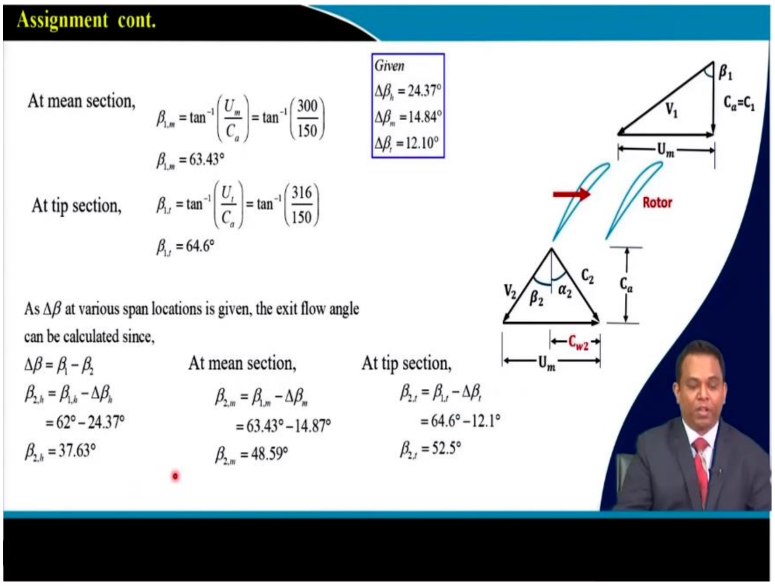

Inline to that you can calculate your β_1 angle at the mid-section and that is coming 63.43°.

$$At\ mean\ section,$$

$$\beta_{1,m} = \tan^{-1}\left(\frac{U_m}{C_a}\right) = \tan^{-1}\left(\frac{300}{150}\right)$$

$$\therefore \beta_{1,h} = 63.43°$$

$$At\ tip\ section,$$

$$\beta_{1,t} = \tan^{-1}\left(\frac{U_t}{C_a}\right) = \tan^{-1}\left(\frac{316}{150}\right)$$

$$\therefore \beta_{1,h} = 64.6°$$

At the tip station you can calculate in a same way and that angle is coming 64.6°. Now, we are given with $\Delta\beta$ at different stations. So, if you look at $\Delta\beta$ at the hub is given 24.37°, at the mid station it is given 14.84° and at the tip station it is given 12.10°.

$$Given,$$

$$\Delta\beta_h = 24.37°$$

$$\Delta\beta_m = 14.84°$$

$$\Delta\beta_t = 12.10°$$

So, based on that we can calculate what will be my exit angle, exit air angle from the rotor. At hub we can calculate that as a 37.63°, at mid-section it is coming 48.59° and at tip station it is coming 52.5°. Now, the angles β_1 and β_2 they are known to us, we already know what is our peripheral speed at different stations, our axial velocity that's what we are assuming to be constant.

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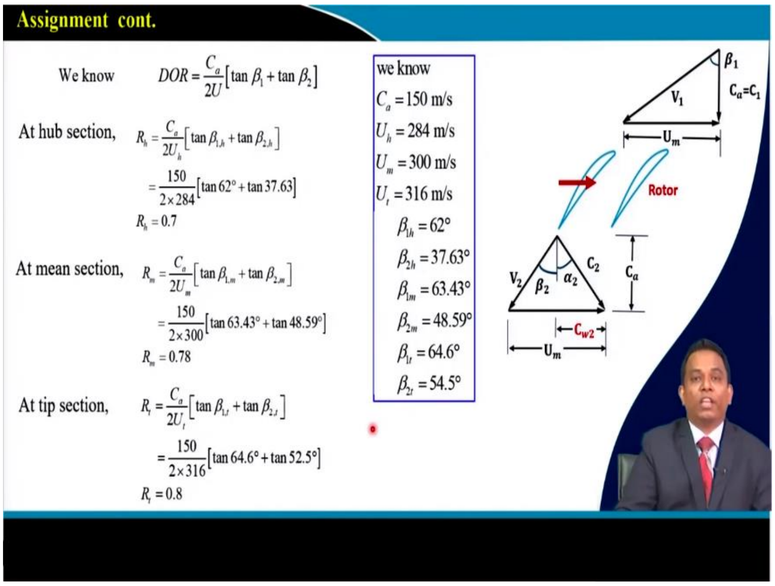

So, based on that, we can calculate our degree of reaction that is

$$DOR = \frac{C_a}{2U}[\tan\beta_1 + \tan\beta_2]$$

Now, for all the stations we have calculated our β_1, we have calculated our β_2.

$$\beta_{1,h} = 62°$$

$$\beta_{2,h} = 37.63°$$

$$\beta_{1,m} = 63.43°$$

$$\beta_{2,m} = 48.59°$$

$$\beta_{1,t} = 64.6°$$

$$\beta_{2,t} = 54.5°$$

So, based on that you can calculate your degree of reaction at the hub. So, if you look at the hub, this is what is given in sense of your peripheral speed at the hub, and these angles are at the hub. So, degree of reaction at the hub, it is coming 0.7.

At hub section,

$$R_h = \frac{C_a}{2U_h}\left[\tan\beta_{1,h} + \tan\beta_{2,h}\right]$$

$$= \frac{150}{2\times 284}[\tan 62° + \tan 37.63°]$$

$$\therefore R_h = 0.7$$

At mean section,

$$R_m = \frac{C_a}{2U_m}\left[\tan\beta_{1,m} + \tan\beta_{2,m}\right]$$

$$= \frac{150}{2\times 300}[\tan 63.43° + \tan 48.59°]$$

$$\therefore R_h = 0.78$$

At tip section,

$$R_t = \frac{C_a}{2U_t}\left[\tan\beta_{1,t} + \tan\beta_{2,t}\right]$$

$$= \frac{150}{2\times 316}[\tan 64.6° + \tan 52.5°]$$

$$\therefore R_h = 0.8$$

So, it is reasonably good number, it is a high number in sense.

Now, if you look at a mean station, my degree of reaction it is coming 0.78 and at a tip station, this is what is coming 0.8. So, this is what will be giving you idea for the calculation of degree of reaction. When we will be doing the design for different types of compressors and fans that time this is what is one of the parameter, that’s what we need to keep on eye. And this parameter needs to be calculated systematically and then that’s the reason why we are having more emphasis on having this calculation as tutorial as well as assignment. Now with this, let us move ahead.

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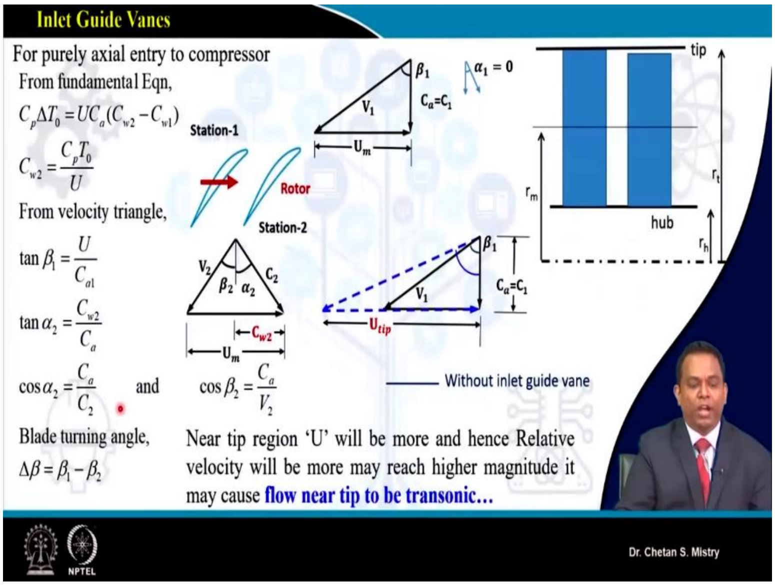

Now, if you recall, we were discussing about the construction of our axial flow compressor. During the discussion about the construction of axial flow compressor, we were discussing about the entry part that is called inlet guide vane. And we have discussed both the side of pacific, means your European and American concept, they have different thought process. Let us try to understand what we mean by inlet guide vane and what are the uses of this inlet guide vane and how do we incorporate for our design, whether we will be going with inlet guide vane or not, that also we will try to understand.

So, from fundamental, what we know, if I am considering purely axial entry, that means my $\alpha_1 = 0$, you can write down my thermodynamic work done and aerodynamic work done, they both are same. Since, this is what is the axial entry, so my C_{w1}, that's what will be coming as 0. Now, if I am putting that the exit swirl velocity, I can calculate based on my thermodynamic work and my peripheral speed. This will help us in calculation of my angle β_1 at different stations, because my peripheral speed, it is a function of radius. So, you can say at the hub station, at mid station and tip station, you can calculate what will be our β_1.

Similarly, we will be calculating our α_2, and we will be calculating what is our $\Delta\beta$. Now, what we learn, with increase of our radius, what is happening? We have our increase of peripheral speed. If I consider my axial velocity to be constant, then we will realize we are having this angle β, that's what is going to increase; not only increase in β, we will be having the increase in our relative velocity.

Now, this relative velocity that's what will be giving our flow to be transonic in that particular region. So, you can understand if I will be putting three different stations; we have seen earlier, at hub station, my V_1, that's what is less, at mid station by V_1 that will be increasing and at the tip station, we will be having our relative velocity to be high.

Now, in order to manage that kind of thing, let us see; we say, I want to reduce my relative velocity, what is the reason because we are looking for our flow to be subsonic or high subsonic near the tip region. Reason is when my flow that's what is going transonic, there may be chances for the formation of shock and this shock we have considered that's what is acting like a blockage to my flow; and that's what is increasing my losses. And that will lead to reduce in efficiency as well as sometimes it is reducing my operating range. So, that is the reason what I will be doing, I am looking for this velocity.

So, if you are looking for that what it says? My peripheral speed I am putting as a constant, that means I need to enter my flow with some absolute velocity like this. That means I am looking for some kind of mechanism that's what will be giving my flow to enter at some angle α_1, okay. Now, when I say, I am incorporating my α_1, that's what will be giving me change in my β_1, okay.

Now, here in this case, we were discussing, say particular about the selection, whether we will be going with inlet guide vane or not. So, let us see what all are the implication of that, if we will consider we are entering our flow at some angle α_1, we will be having swirl component at the entry. That is nothing but my C_{w1}.

Now, what we have assume earlier? We have assumed our flow, it is entering axially. So, in that case, we have removed the C_{w1} component. Now, we are purposefully giving C_{w1} components. So, you can see, in this equation ($C_p \Delta T_0 = UC_a(C_{w2} - C_{w1})$, what it says by incorporation of my C_{w1}, that's what is lead to reduction in my compression work; that means the pressure rising capacity of my compressor that will be reducing. So, in other sense, what pressure we are looking for, in order to achieve that pressure rise, it may require to increase the number of stages.

So, by incorporating this inlet guide vane you can say, you are looking for more number of stages. And if you are not incorporating, it may be possible that, that will lead to reduction in number of stages. And that's what is helping us in sense of achieving what we are looking for in sense of compactness, in sense of reduction of weight, in sense of having your operating range and fuel economy. So, just understand, we are looking one of the aspects; what it says? We want to reduce our relative velocity near the tip region and for that we are incorporating our, say inlet guide vanes. But it is reflecting straightway in sense of my pressure rising capacity, okay. Now, let us move with say next configuration. Here if you look at this red color, that's what is representing with inlet guidance, what is happening.

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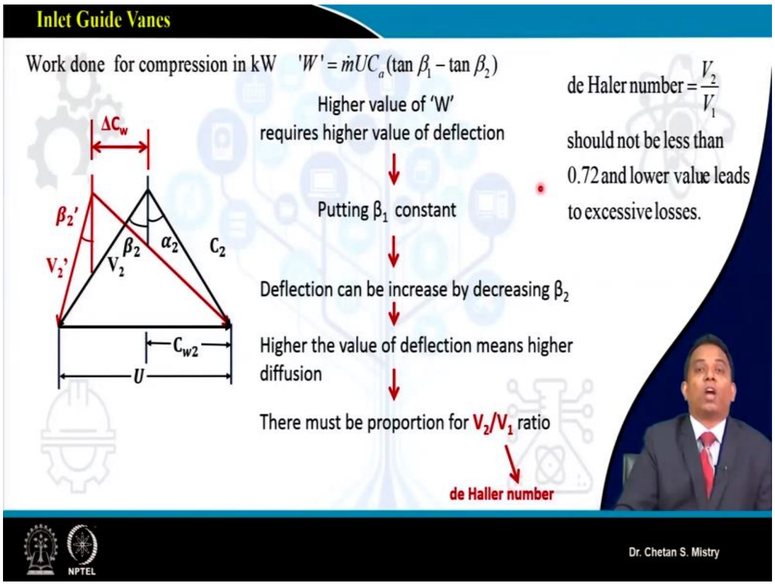

Now, let us move to the next step. What it says? My work done for the compression, that's what is represented by

$$W = \dot{m}UC_a(\tan\beta_1 - \tan\beta_2)$$

Suppose say, if you are looking for high work; you can say, you are looking for high compression ratio. Now, work I am correlating with my compression ratio. If that's what is your case, and my β_1, if I am assuming to be constant, that means it is a function, that's what is correlating my, axial velocity and peripheral speed.

I say, I am putting my β_1 to be constant. What it says, in order to achieve high work, you need to decrease your β_2. So, here if you look at, this is what is say my original velocity triangle; in which we are having our relative velocity V_2, and my blade angle at the exit or my air angle, relative air angle, that's what is β_2, that's what is at the exit.

And as per our understanding from our fundamental equation, what it says? We want to reduce our β_2. So, this is what is a configuration, it says I am reducing my β_2, so what all is happening; you just look at, by doing that, you are able to increase your ΔC_w that is what we are looking for.

But at the same time, what is happening? Just look at, my absolute velocity component that's what is going to be increase, okay. So, it says, you will be able to achieve higher diffusion by reducing your β_2. Now, there is a proportion for having this reduction in relative velocity at the exit of rotor. It says there must be some proportion of your ratio V_2/V_1 and that number that's what is defined as 'de Haller's number'.

So, meanly he is a British scientist, who was talking about the proportion for the relative velocity. So, if you look at, say we have discussed, like diffusion factor is one of the parameter in order to calculate how the diffusion that's what is happening with your compressor. That parameter we are considering, we are calculating at the design stage.

So, in line two that, people in Europe, they are considering this relative velocity ratio, this de Haller's number as catch on eye and according to de Haller, this number should not be more than, it should not be less than, it should not be less than 0.72 and lower value of this that will lead to excessive losses.

So, now you can understand for the design, we have introduced our first parameter that's what is diffusion factor, we have introduced our second parameter, that's what is degree of reaction and today we have introduced our third parameter, which need to be catch on eye and that's what is de Haller's factor or de Haller's number.

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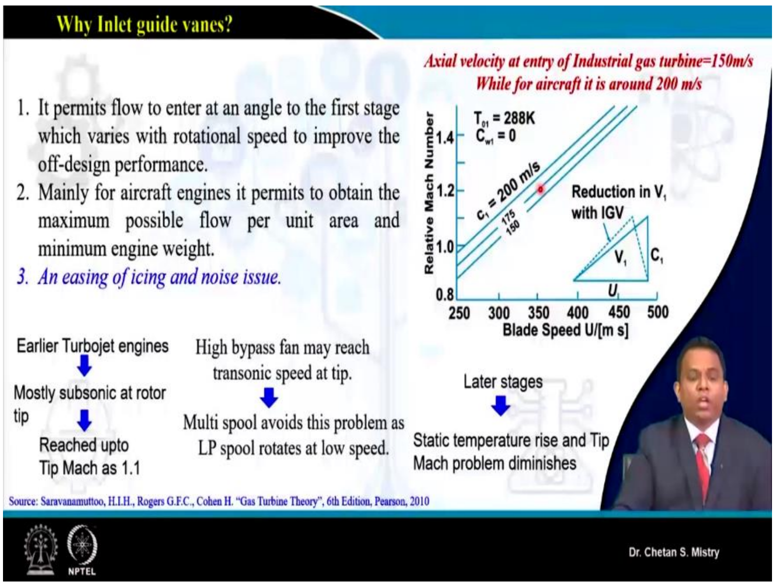

Now, in order to understand what all are the reason why we are going with inlet guide vanes? So, if you look at, doing earlier design, say mainly for turbojet engines, as we were discussing, those all compressor rotors, they are mainly subsonic rotors. And they were trying your rotor not to reach to transonic range and they reach up to tip Mach number of around 1.1.

So, that's what was the whole thought process and later on during 70s people they are realizing in place of having control on this relative Mach number by rotating the wheel at low speed, we need to think of some other alternative and that's what has given the idea of incorporation of different transonic airfoils.

So, here if you look at, for most modern high bypass ratio engines, they are having transonic airfoils, okay. And if you look at, they are using multi spool configuration, which will lead to rotate your LP compressor at low speed, same way your fan also will be rotating at low speed. If there are any chances for the formation of shock, that's what has been taken care by designing special kind of transonic airfoils, okay. And you know, now, let us try to understand what we are talking about reaching of Mach number in transonic range or supersonic range.

So, at the entry condition, if you are looking at, my Mach number at particular station, in sense of relative velocity, it is given by $V_1/\sqrt{\gamma R T_1}$, at the entry my temperature is lower. Suppose if I am considered for aero engine at altitude, my T_1 will be lower; that means, there is a chances that my flow will go transonic at the entry station.

Now, in last lecture, I was showing you the blades for HP compressor and there I was talking to you saying like those blades are of subsonic kind, what is the reason? When I am increasing my pressure ratio means from LP spool to HP spool, if I am going, I am increasing my pressure ratio, with increase of your pressure, my temperature also is increasing.

That means in the denominator term, it says when I am calculating my relative Mach number, that is what never be reaching to this transonic range. And that's what is giving us idea like my high speed or HP compressor, that's what is of subsonic kind of blades, okay. Now, here if you look at, this is what is a plot that's what is relating your blade speed, your axial velocity and your relative Mach number. Suppose if I consider, I am not incorporating inlet guide vane, my axial velocity and absolute velocity that's what is same.

What is our requirement? We say, we want to increase the rotational speed of our wheel, that means I will be increasing from 300 to 350 or may be 400. What is happening for particular say… axial speed? We will be having our Mach number, that's what we will be going in a transonic range. So, it says maybe you need to reduce with your blade speed. If I am reducing my blade speed, you can understand, we are reducing our per stage pressure ratio. Because, your work done, that's what is directly related with your peripheral speed, okay. And here if you look at, if I will be going with higher blade speed and you know, higher axial velocity, it is definite that my flow will be going say… in a transonic range.

So, roughly it says for industrial compressors or industrial gas turbines, the axial velocity is roughly been counted as 150 m/s. And for say your aero engines, this speed that's what is or axial velocity, it is counted as 200 m/s. Now, as we were discussing, what are the use of guide vanes? So, it says, it permits the flow to enter at the angle, for the first stage that's what will be giving the improvement in off design performance. So, if you look at, suppose I am talking about aero engines, these aero engines are working under different conditions; we can consider it is working under say… take-off condition, cruise condition and landing condition.

If I am talking about aero engine, that's what is applicable for military purpose, we will be having subsonic cruise, we will be having supersonic cruise, we will be having maneuvers. So, all these conditions, what is happening, it may be possible that your speed or rotational speed of your compressor that may be varying.

So, under that condition, you are looking for your thrust to be enhanced, and that's what is been controlled by using these inlet guide vanes. So, for this purpose, this inlet guide vanes are made as variable inlet guide vanes. So, this variable inlet guide vanes, it will be taking care of what all changes in mass flow rate that's what is happening.

These days, people, they started talking about the sixth generation aircraft, that's what is variable cycle engine; and it is particularly, this inlet guide vanes, they are been fitted with. Even in a later stage also, they people, they are using say variable guide vanes, okay. So, this is what is a main requirement. So, you can say, by incorporating these inlet guide vanes, you are basically, you know, enhancing your performance even in off design condition, okay. Now, it says this is what is giving maximum possible flow per unit area and that's what is giving the minimum engine weight, okay.

Next issue, that's what is it is addressing, that's what is easing of icing. So, when you are flying at altitude or maybe when you are moving towards say on western side; so, you will be finding the temperature is lower. So, this inlet guide vanes, they are being provided with some heaters. So, that's what we will be taking care of avoiding the ingestion of ice particle inside the rotor inside the engine. It is also taking care of noise, that's what is generated by the rotation of your say fan or maybe for your LP compressor. So, these all are the purposes for which inlet guide vanes they are being used.

So, we need to be very careful, say what is our purpose? Why we are making these engine? What are the applications of these engines? And, based on that we need to think of whether we will be incorporating our inlet guide vanes or not, okay. So, this is what is designer's choice and requirement by the customer.

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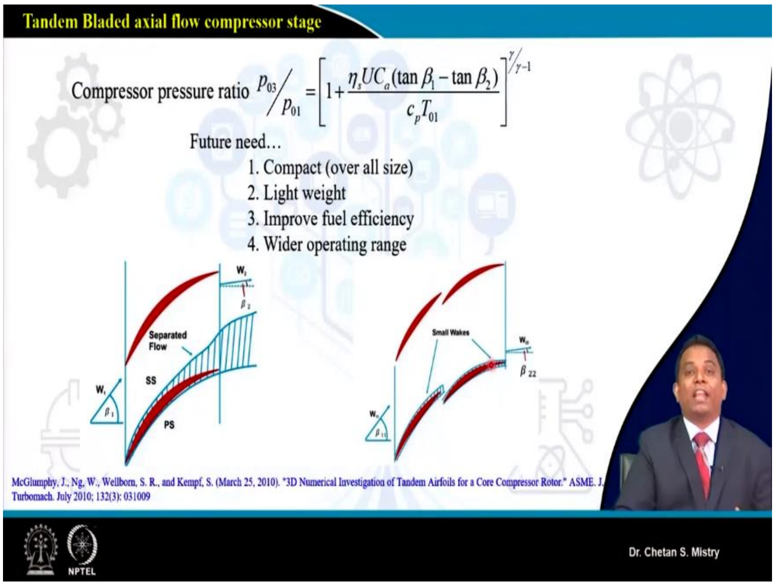

Now, we were discussing different approaches for enhancing the pressure ratio or per stage pressure rise. We can improve that per stage pressure rise by different ways. We have discussed, we can go with increasing our peripheral speed, we can go with increase of our axial velocity, we can go with increase of my $\Delta\beta$, okay. What is the reason? Because, these days we are having trend of compact engine that means overall length need to be low, we are looking for lightweight engines, we are looking for improvement in fuel economy, we are looking for wider operating range.

Let me tell you again and again, this axial flow compressor application to aero engine, they are having these specific requirements. When I am talking about application for land base power plant, they have some relaxation in these aspects, their major concern it is in sense of fuel economy. So, if I will be discussing about the different aspects, we were discussing about say deflection angle to be higher. So, here if you look at, my flow that's what is entering at some angle β_1 and it will be leaving at some angle β_2. Now, here if you look at, this particular blade or this particular airfoil at particular station, that's what will be having higher $\Delta\beta$.

We are looking for higher $\Delta\beta$ in order to increase our pressure rise. Since this is what is working under adverse pressure gradient, means my inlet pressure is lower, my outlet pressure is higher; there are chances that my flow will get separated from the substance surface. So, here if you look at, because of higher deflection angle, you can say, highly cambered airfoil that's what we will be giving you the flow separation that's what is happening, that's what is defined as a stalling of airfoil.

For compressor, we can say, it is a stall of my blade. This stall, that will continue for some time that will convert it into surge. And that's what will lead to catastrophic failure of your engine. And that is the reason, again let me tell you, the compressor, it is a heart of engine if this is what is not working fine, your engine that will not work, and that's what is very important, okay. Now, in order to address these issues, people they started exploring the concept, that's what is called tandem bladed concept. So, what is that actually? You know, the whole deflection of this single blade, that's what will be converted by using two blades, they are arranged in a particular systematic manner.

So, here if you look at, this is my first blade, this is what is my second blade, you can consider these two blades it is making single blade. Do not get confused, this is what is single rotor blade. What it will be doing? If you look at, this is what is reducing the thickness of my boundary layer, that's what is growing on the suction surface. And here if you look at, this is what is a small passage between these two airfoils and that's what will lead to flow to get accelerated within this passage, okay.

Once my flow is getting accelerated, that's what will lead to, you know, avoid the flow separation from my second blade, okay. So, I will be having my flow that will be sticking on the surface. So, this is what is a concept what people they are exploring these days, that's what is called tandem bladed concept.

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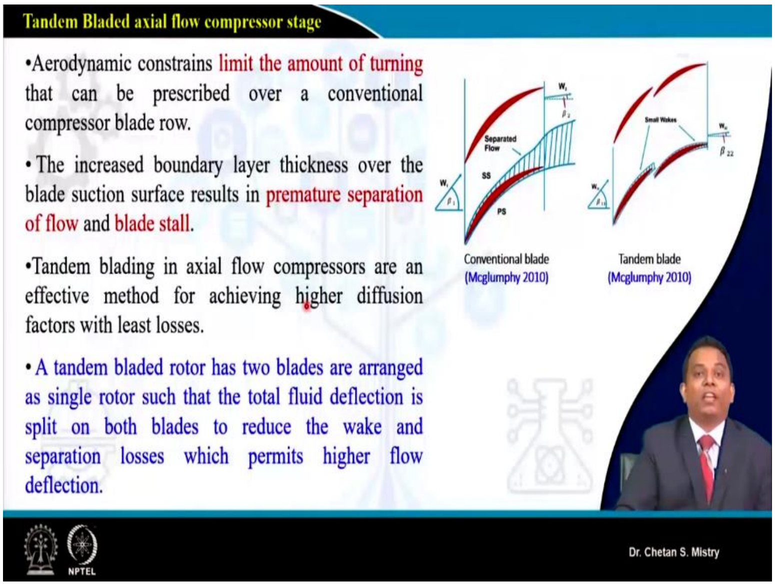

Now, as I told you, we are having limitation because of high turning; and because of that high turning you will be having more chances for your flow to get separate. And to avoid that kind of separation, we are discussing about the tandem bladed configuration, okay. Now, what all you are looking at, at this moment, that’s what is talking about arranging our airfoils in a systematic way, okay.

So, you know, like this angle, what we are talking about $\Delta\beta$; we know, that’s what is changing all the way from my hub to tip, okay. So, I will be having my $\Delta\beta$ at hub, I will be having my $\Delta\beta$ at the mid-section, I will be having my $\Delta\beta$ at the tip section. And all that station, my $\Delta\beta$, they are different. So, I need to be very careful, while I will be incorporating my tandem configuration for development of rotor and stator.

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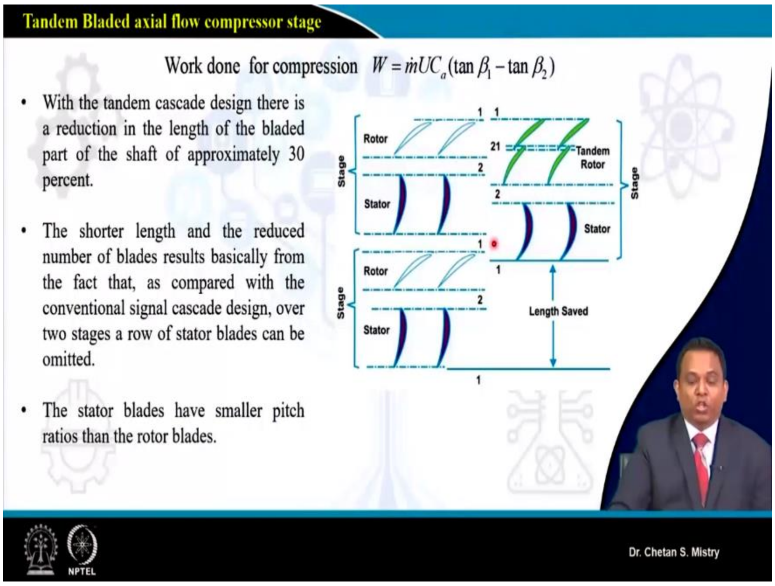

So, what it says? Say, if you look at this diagram, so this is what is representing two stages, say rotor and stator combination, that's what is my first stage and this is what is my second stage. Now, what it says? A research and development activity, that's what was going on, that's what is recommending, by using this kind of configuration, it may be possible that we are able to reduce the length of our shaft by 30 %. Now, you can understand, when I am looking for the compactness, when I am looking for the low weight, if I am a reducing my length of the shaft by 30 %, you can say I am able to reduce my weight, even!

You know, here if you look at, we will be having, say in place of two stages, maybe one stage will work for you. And that's what will be reducing your number of stages required. Again, when I am reducing my number of stages required, that's what will be reducing my number of components to be used in my axial flow compressor that's will be reducing my number of stator blades, number of rotor blades. Again, that will be helping in sense of reduction of my weight, okay. So, if we are able to do a systematic design, by using this concept, this is what is more promising in sense of achieving high pressure ratio, okay.

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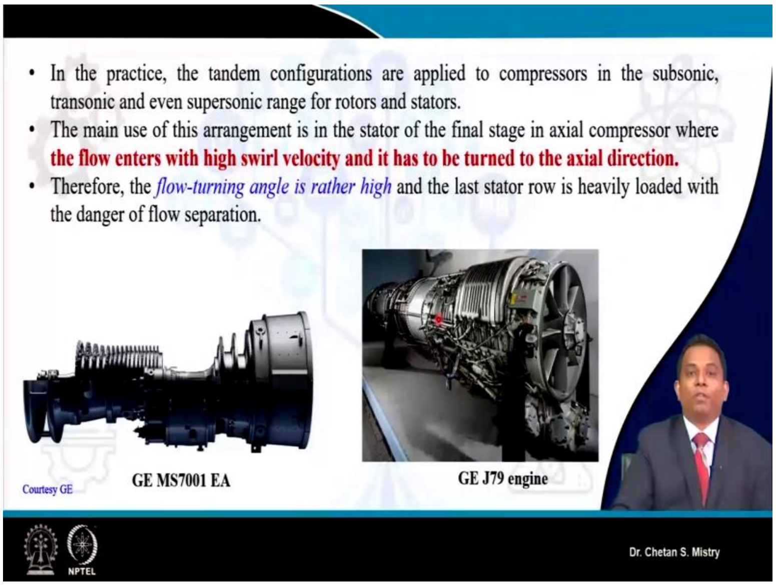

So, people throughout the world, they people, they are working on application of this tandem blade configuration for subsonic, for say transonic, even for a supersonic kind of axial flow compressors. Mainly, the end or we can say HP compressor and at the entry of your combustion chamber, your flow will be having high swirl and you want to divert, you need to transfer your air to the combustion chamber in axial direction. And that's where if you are looking at, my blade turning requirement by the stator it is very high and there are more chances for the flow to get separate in that particular region. And that is the reason why GE they have developed their engines.

So, this is what is one of the land base power plant in which they have incorporated their last stage stator, that is of tandem configuration. In line to that, they have applied that for G 79 engine also. So, you can understand now, people they started, they are started using this concept. There are many more companies, they may be working or they already have implemented this kind of configuration in their engine, but because of proprietary nature, it may not be available in open literature, but you can understand this is what is one of the promising concept.

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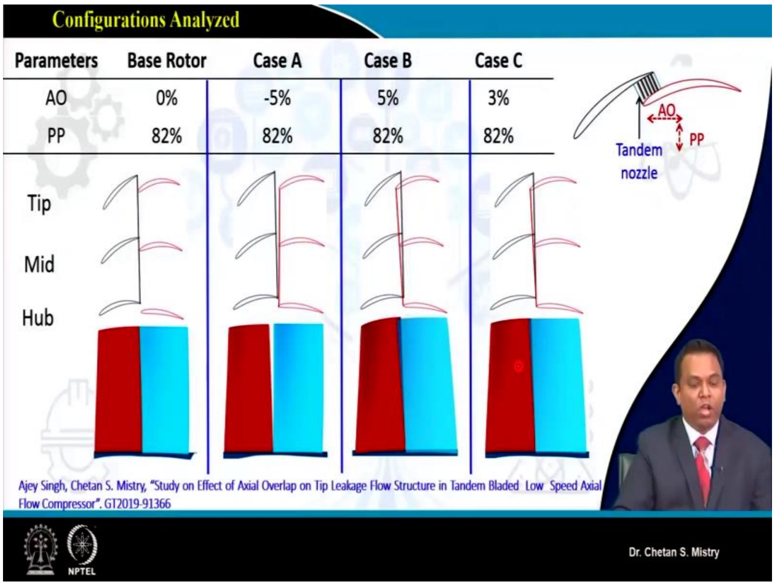

Now, if you are looking at this promising concept, based on that at IIT Kharagpur, we started working on development of tandem bladed configuration. So, one of my PhD students, he is working on development of tandem bladed, say rotor. So, initial stage if you look at, this is what is a configuration. It says we are having two blades which are arranged in a particular way; it says it is having, so, here if you look at, this is what is say my front blade and this is what is my rear blade. Now, here if you look at this has been arranged in such a way, so, you know, the distance between my trailing edge of front rotor and leading edge of my rear rotor, that's what we are defining as say axial overlap.

The distance or circumferential distance between these two blades, that's what is defined as a percentage pitch. So, for design purpose, we have taken our percentage pitch to be 82%. And we have varied the axial overlap, that's what is vary from 0 % to 5 %. So, if you look at, my leading edge and trailing edge, they both are arranged in line for 0 % axial overlap; you can understand when I say I am moving my rear blade away from my trailing edge near a tip region, that's what we have defined as -5%.

In line to that, we have explored with +5, that means my rear blade, that's what is moving towards the front blade; it is inclined towards the front blade near the tip region and here this is what is with 3% axial overlap. So, more details, that's what is available in one of the turbo export paper those who are interested can go through that. Let me show you this blade.

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Here if you look at, here if you look at, these are the two blades, you can see; this is what is my front blade, this is my real blade. You can see here, I am having this is my leading edge, this airfoil it has been stacked about the CG; and if you look at carefully, see our axial overlap, here, this is what is varying. So, if you measure your distance this is what is my axial overlap.

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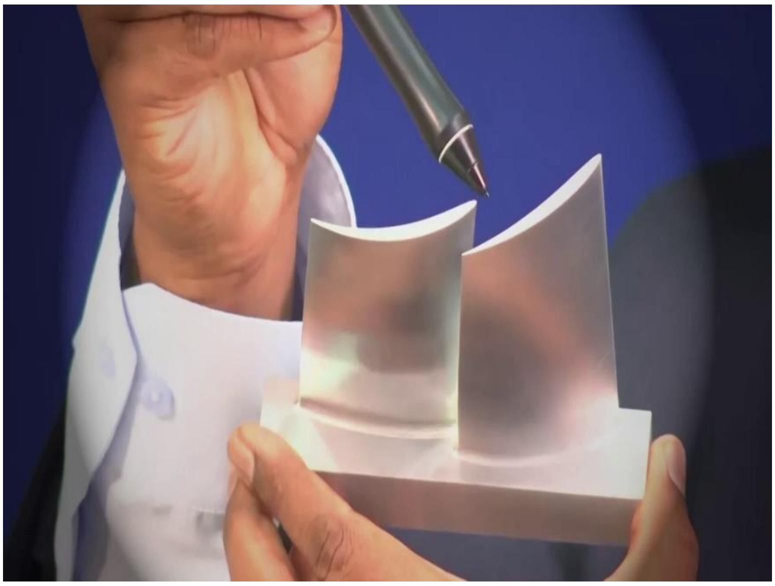

Near the hub region, if you try to look at, my axial overlap it is zero and here this is what is 3%, okay.

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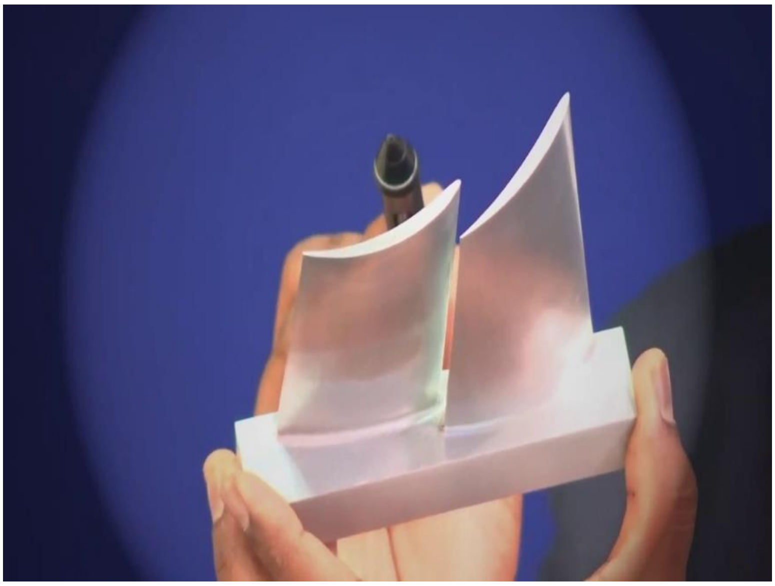

Now, what we learn from our basic understanding, say we need to provide certain amount of gap between these two airfoils such that it will give me, say action, that’s what is called nozzle action. So, what all reported study we are having those reported studies are talking about the cascade; but when we are working on actual configuration, you can see, from hub to tip, I will be having different angles.

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And I need to manage my flow throughout my span, and in order to take care we need to change our axial overlap, okay. So, this is what is tandem bladed rotor. So, the experimental work that’s what is going on for this particular rotor along with the stator. In next lecture, I will be showing you the stator that’s what has been designed for this particular rotor.

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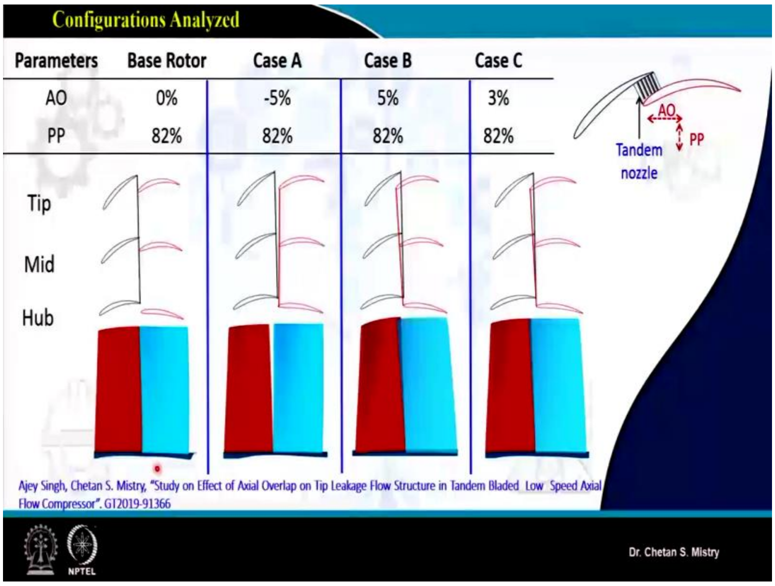

So, thank you very much for your attention! And I am sure, what all we have discussed today, that’s what will be helping you in sense of understanding what we mean by inlet guide vane, what all are the purposes for inlet guide vane and how people they are thinking of application of inlet guide vane for recent and future engines. Thank you! Thank you very much!