Aerodynamic Design of Axial Flow Compressors and Fans
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Lecture 8
Stage Configurations and Parameters (Continued)

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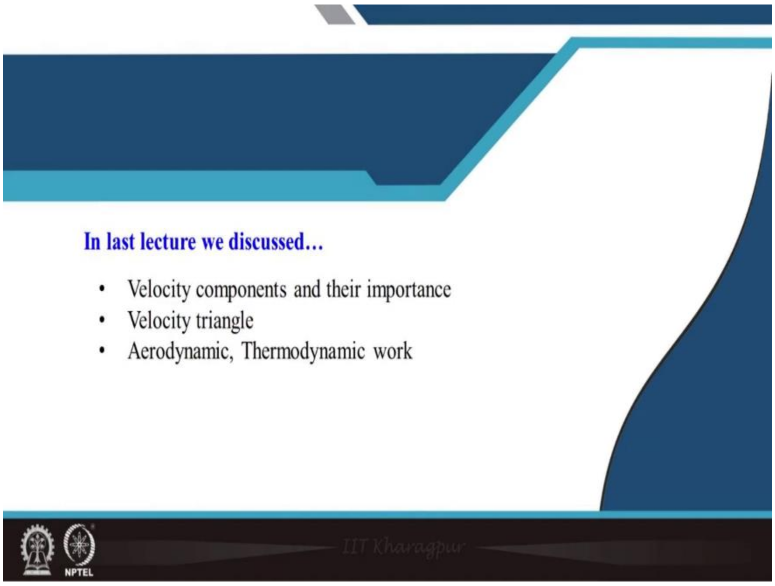

Hello, and welcome to lecture-8. In last lecture, we were discussing about say… velocity components and their importance for axial flow compressor. We have discussed about the velocity triangle; we started with talking about incorporating the component that’s what is called inlet guide vane, and then what is the modification in our velocity triangle. We have discussed about how you will be having different velocity triangles at different span or different location, that’s what is at the mid-section, at the hub as well as at the shroud.

And we realize what all is the use of this velocity triangle and what is the reason why we are having our variation in blade angles, that’s what is starting from hub to shroud. Let me tell you, say, people they are having understanding of aerodynamics of airfoil. The understanding of fundamentals of airfoil, that’s what is applicable to this axial flow compressor; but, you can realize, this is what is not a two-dimensional body. Because of variation of your radius, we are having our blade that will become three-dimensional body.

So, the concept that’s what is applicable; but you know, my whole flow physics, in sense of understanding, in sense of aerodynamics, that’s what is totally different. It has nothing to do with what airfoil we are discussing about the way, okay. So, now onwards when I say airfoil, just be clear, we are talking about the airfoil, that’s what is used for axial flow fan, or say axial flow compressor. Then we started talking about the work done correlation, that's what is representing your case for, say, aerodynamic work and your thermodynamic work.

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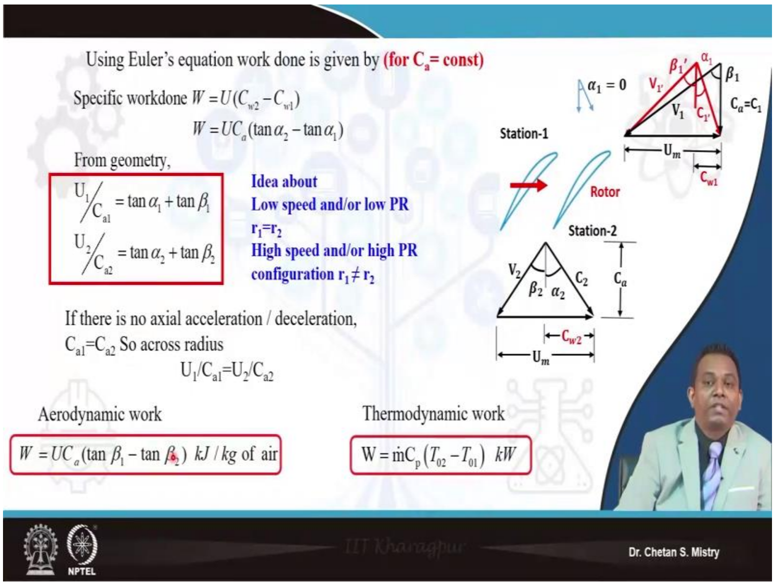

Now, this is what we have derived, this is what we were discussing about, say…my, you know, specific work done using my aerodynamic correlation using my velocity triangle, that's what can be written as

$$W = UC_a(\tan\beta_1 - \tan\beta_2)$$

We have our fundamental understanding of thermodynamics, what we discussed in our last module, okay. Now, let us move ahead, what all will be the use of these relations, okay?

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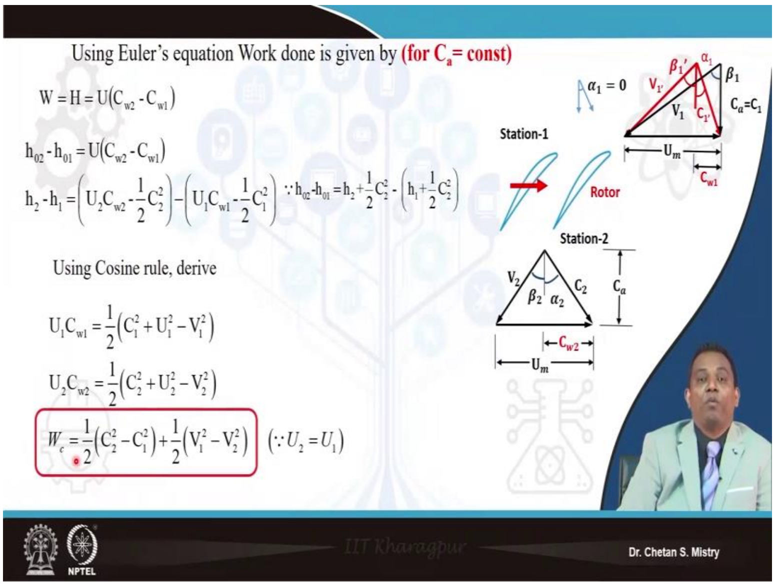

So, what we know from our Euler's equation, my work done, if I am assuming my axial velocity to be constant, that's what it is been represented by, you know,

$$W = U(C_{w2} - C_{w1})$$

Now, you know, if I am correlating this aerodynamic work with my thermodynamic work, that's what can be represented as say,

$$h_{02} - h_{01} = U(C_{w2} - C_{w1})$$

This is nothing but $C_p(T_{02} - T_{01})$. This total enthalpy, that's what we can represent in sense of static enthalpy and my velocity components. So here, we can write down this is what is given by $h_2 + \frac{1}{2}C_2^2$ and this is what is $h_1 + \frac{1}{2}C_1^2$, okay. And if I will be putting in this equation, that is what will be giving me correlation in sense of my peripheral speed, in sense of my say… whirl component and my absolute velocity.

$$h_2 - h_1 = \left(U_2C_{w2} - \frac{1}{2}C_2^2\right) - \left(U_1C_{w1} - \frac{1}{2}C_1^2\right)$$

Now here, in this case, if I will be using my fundamental understanding of trigonometry, and if I am using my cosine rule, it says, U_1C_{w1}that's what is given by $\frac{1}{2}(C_1^2 + U_1^2 - V_1^2)$, at the exit I can write down U_2C_{w2} that's what is $\frac{1}{2}(C_2^2 + U_2^2 - V_2^2)$, okay. And if I will be putting all together, that's what is giving me my work done as,

$$W_c = \frac{1}{2}(C_2^2 - C_1^2) + \frac{1}{2}(V_1^2 - V_2^2)$$

And let me assume my peripheral speed U_2 and U_1, that's what is equal.

Now, we have seen in last lecture that my U_2, and U_1 may not be same when I am talking about the high-speed compressor when I am talking about high pressure ratio compressors. But at this moment in order to understand this is what is representing my third way of work done. So first we can represent by using aerodynamic fundamentals. Second, we can discuss by using the aerodynamic work done.

And this is what is representing in sense of your kinetic energy. And this is what is you already know. What we know? Here if you look at, this is what is representing my relative velocity at the entry, this is what is representing my relative velocity at the exit. And what we realize? My relative velocity at the entry, that's what is larger, okay; and, my relative velocity at the exit that's what this is say… smaller. Now, if that's what is your case, you can say, this is what is responsible for doing my diffusion work, okay. So, you know, like your diffusion, that's what is been represented in terms of my relative velocity components.

Same way, if you look at, my absolute velocity with which flow is entering inside my rotor, and absolute velocity with which my flow, that's what is coming out from my rotor, that's what is represented here. So, here you know, my absolute velocity, that's what is larger at the exit of my rotor, and my absolute velocity is lower at the entry of my rotor, and that's what is represented here. So, you know like, this is what is also one of the ways to understand the work done component. This is what is very important, we, when we will be discussing about the different kinds of stage configuration. We will be discussing in detail in next session, but at this moment, just realize, this is also one of the way to represent our compressor work, okay.

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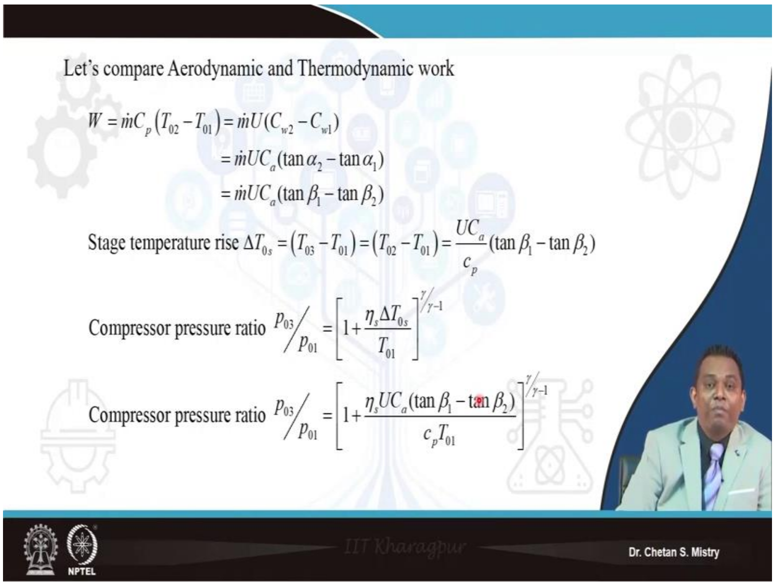

Now, if we compare our aerodynamic work and thermodynamic work; it says this is what is $\dot{m}C_p(T_{02} - T_{01})$. This is what is representing my aerodynamic work, it is $\dot{m}U(C_{w2} - C_{w1})$. And as we have seen, this is what can be represented in sense of your absolute flow angle, that also can be represented in relative flow angle, okay. So, this is what is representing my relative flow angles, $\beta_1 and\ \beta_2$.

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

Now, let me compare these two equations, I can write down my stage temperature rise, that is nothing but $T_{02} - T_{01}$, that's what is given by $\frac{UC_a}{C_p}(\tan\beta_1 - \tan\beta_2)$. Now, here, let me put this $\beta_1 and\ \beta_2$, we can say that's what is say $\Delta\beta$, okay, that is nothing, but the change in my relative flow angle, change in my relative air angle, okay.

Now, what we know, our compressor ratio, or compressor pressure ratio, that is what we can represent in sense of my, you know, stage efficiency or isentropic efficiency into $\left[1 + \frac{\eta_s \Delta T_0}{T_{01}}\right]^{\frac{\gamma}{\gamma-1}}$. Now, let me combine these two equations in place of ΔT_0 , I will be writing $\frac{UC_a}{C_p}(\tan\beta_1 - \tan\beta_2)$.

$$\frac{p_{03}}{p_{01}} = \left[1 + \frac{\eta_s UC_a(\tan\beta_1 - \tan\beta_2)}{C_p T_{01}}\right]^{\frac{\gamma}{\gamma-1}}$$

So, here if you look at, my pressure ratio, this is what is a function of all these parameters. Now, this is what is very important, this is very important for us to realize, okay, how we will be getting our pressure ratio. So, let me move to say our next slide.

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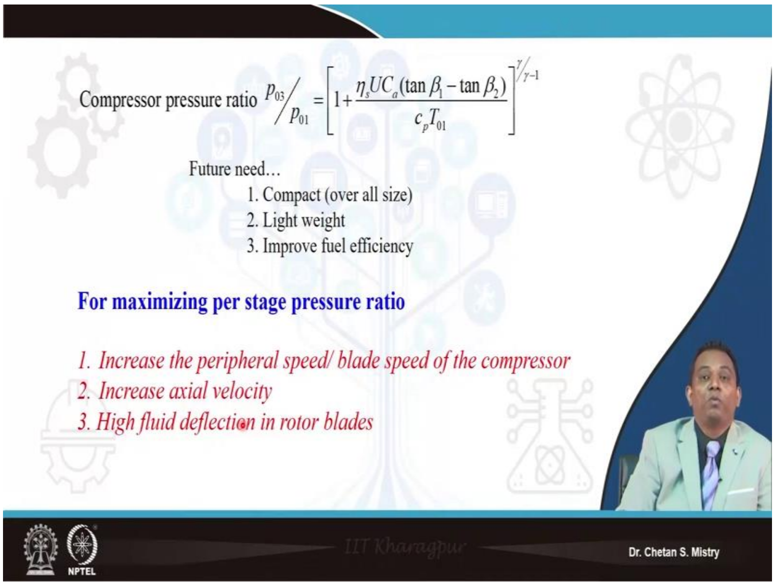

Say, this is what is representing our compression ratio as we have discussed. Now, let us discuss about what all we are expecting from our compressor application to aero engines, okay. Now, what all we are looking for our future engine, we are looking for compact engines. That means I want to reduce the overall size of the engine.

That means if I consider, I want to reduce the number of stages, that's what we are using in axial flow compressor. And we have realized when I was discussing polytropic efficiency, it says you increase the number of stages such that you will be getting higher overall efficiency.

Now next, that's what is lighter weight of our engine, because that's what is directly related with your drag of the engine, drag of your aircraft. And that's what is directly related with your fuel economy. That means your pressure ratio, that's what is always a major parameter in order to design your engine, okay.

When I say, I am looking for this kind of situation, it says I am looking for per stage pressure rise to be large; I am looking for per stage pressure raised to be higher. If my per stage pressure raised, that's what is higher, I can reduce the number of stages required to do particular compression. If I am reducing the number of stages, that's what is reducing my overall length and weight of the engine; that's what is my requirement.

So, now the thing is, based on this correlation; if you look at, it says per state pressure rise if I am looking to be increased, so if we look at, this is what is representing my entry temperature. So, you can understand for aero engine; since, it is flying at different altitude, say… ground condition, cruise condition; those conditions are different.

So, my T_{01}, that's what is you can say it is my atmospheric condition; that's not in our hand, okay. Now, if you look at here, this is what is representing my isentropic efficiency, my adiabatic efficiency and we have realized, that's what is basically depending on how many stages we are incorporating, okay, and how good design we are doing, because this is what is basically correlating losses, okay. So, if we are able to reduce the losses, that's what is happening in my compressor, we can improve the efficiency, okay.

Next component, it says my peripheral speed. So, what it says, If I am looking for per stage pressure rise to be large, I need to increase my peripheral speed. So that's what it says in order to maximize per stage pressure ratio, increase your peripheral speed or your blade speed, okay.

Next component, if you look at, that says like my axial velocity. So, what it says? If I am increasing my axial velocity, I am able to increase my pressure ratio, okay. And, as I told, this is what is representing my $\Delta\beta$, okay, that is nothing but my blade deflection angle, how I am deflecting my flow, what angle I am putting at the entry and exit, that's what will be deciding my $\Delta\beta$, okay. So, it says higher fluid deflection in the rotor blades. So, now you can understand, what all we are looking for, we are moving towards the solution, okay. What solution we are looking for? We want to have high per stage pressure rise. So, let us discuss one by one.

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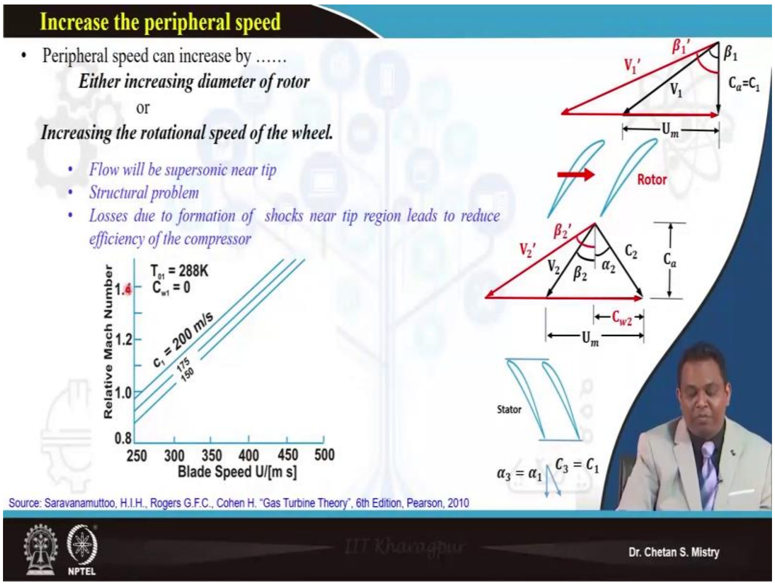

Suppose if I consider, say… first case, I want to increase my peripheral speed. Now, when I say, I want to increase my peripheral speed, you know, we are having two options. First, that's what is you increase the diameter of the engine or diameter of your compressor, okay. Second, it says increase your rotational speed. So, both the options seems to be easy in that sense. So, let us have a look at; this what is say my velocity triangle at one of the station.

And as per the recommendation, if you look at, I am increasing my peripheral speed, okay. So, you can see this is what is increase of my peripheral speed; either I can increase my rotational speed or by increasing my diameter. So, what is happening? Here if you look at, my relative velocity component at the entry of my rotor, that's what is going to be increased, okay. Same way what is happening at the exit of my rotor? Because I am increasing my peripheral speed, my relative velocity at the exit of my rotor also will be increasing.

Now, you know, this is what is a tricky case, okays. What is happening? Suppose this is what I am putting my velocity component or my velocity triangle at the midsection. If I am moving towards the tip, what will happen? I will be having this V_1 component to be very large, that will go in transonic or supersonic range, okay.

So, what it will be doing? My flow will go supersonic near the tip region. Now, as we know, our rotor, that's what is a cantilever kind of configuration. So, your rotor blade, that's what will be fixed on my hub, and other end, that's what is free. So, in case of such situation, we will be having more chances for my structure damage to happen. It will give you problem, that's what is called flutter of my blade, okay; that's what is, you know, aero structural kind of configuration. That is what people used to say 'Aero-Elasticity', that's what is a critical problem, okay. So, it says when I am having my rotational speed to be larger, it has a limitation in sense of my structural problem.

Second, it says, we will be having formation of shock that will be happening near the tip region. Now, we realize this shock is nothing but that's what is increasing my irreversibility in the process, that's what is creating the blockage to my flow in that particular region. And if that's what is your case, what will happen? You will be having your efficiency to be lower, because my losses are going to increase, okay.

So, this is what is one of the plot, that's what is giving you idea how you will be deciding your entry absolute velocity, okay. Since, this this is what is representing my relative Mach number, on my x axis, that's what is representing my blade speed. So, this will give some idea what all numbers you need to decide with. So here if you look at, if I will be increasing my absolute velocity, suppose say… my entry is axial entry, if I am using say… 200 m/s, and if I will be moving with say… increasing my blade speed, you can say, my relative Mach number that's what is going to be high. And that's what is your case, you are having other kinds of problems.

Now, at this moment, I am saying increasing your speed, that's what is creating trouble in sense of formation of shock and that's what is reducing your efficiency. And, people they use to avoid that kind of situation, but with the development of technology with the use of your computational tool, with sophisticated instrumentations use in your experimental part, now, we are able to achieve very high pressure ratio with minimum losses by using special kind of airfoils, okay. Those airfoils are called transonic airfoils, okay, by using these transonic airfoils you are able to address this problem, okay.

So, in… from beginning if I will be talking about all those stuffs, then you will be having confusion what all we are discussing at this moment, but just try to look at, try to understand this is what is one of the problem. So, problem is with my structure, problem is with my rotational speed and problem that's what is with my shock formation. So, it says higher rotational speed that's what is a little tricky. Now, what all people they are working at this moment?

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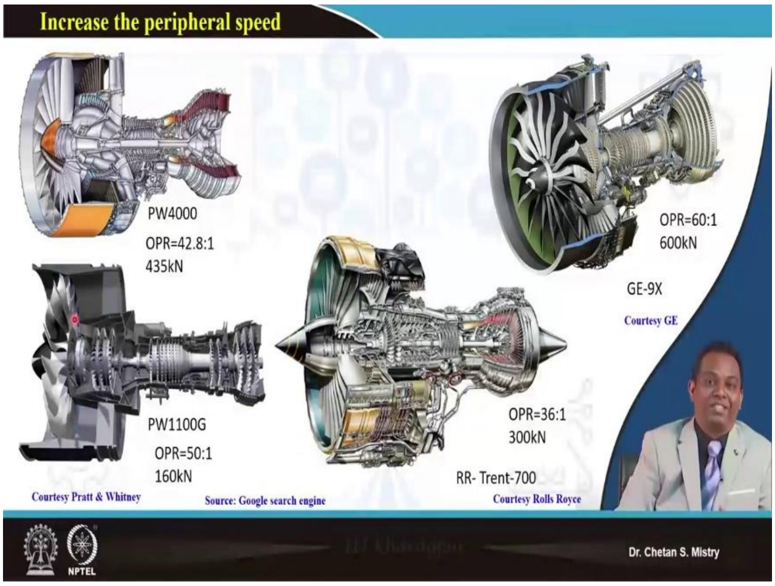

So, you know, these are different engines by different companies. If you look at, this is what is representing Pratt and Whitney 4000, that's what is happening overall pressure ratio of 42.8 and your thrust is roughly 435 kN. Now, what we are discussing? Here if you look at, this is what is my fan, that's what is having pressure ratio roughly in the range of 1.4 to 1.6. This is what is say my LP spool, this is what is my HP spool, okay. And, this HP spool that's what is connected with my HP turbine, my LP spool and fan that's what is connected with my LP turbine.

Now, just look at, okay, here if you look at, this stage, what we are having, that's what we say LP compressor, that's what is having larger diameter, okay. And, if you look at here, for HP spool, my diameter is coming to be lower, okay. Do not get confused in order to have a good look of engine people they have done like this. No, this is what is with your fundamental understanding. What fundamental understanding? That's what is your Euler's equation, okay. What it says? My work done or my pressure rise, that's what is a function of my peripheral speed. So, if I am increasing my diameter here, you know, I will be able to achieve a high-pressure ratio.

Remember one thing, say… your LP compressor is does not mean that it is making or it is generating low pressure, HP compressor does not mean it is generating more pressure or high pressure, okay. It may be possible that LP compressor will be generating more pressure compared to your HP compressor, but here you can see. So, in order to rotate my fan at a lower speed, okay, this spool - LP spool, that's what is rotating at the low speed and that is the reason why this diameter is coming to be large.

Now, for HP spool if you look at my rotational speed will be larger, it will be higher. It may be more than 12,000 RPM and for fan maybe rotating around say 2500 or may be 3000 RPM, roughly, okay. So, since my rotational speed is higher, that is the reason why my diameter is going to be lower, okay. So, this is what is we need to realize in sense of engines. Now, here if you look at, this is what is representing my GE-9X engine and if you look at, that's what is having say thrust capacity of 600 kN and pressure ratio of 60:1!

Now, in this case also, if you look at carefully, this is what is giving me special provision in which I will be having number of stages to be lower. Just look at here, pressure ratio that's what is in the range of 42.8 and just look at this is what is 60:1, okay.

Same way, there is other company that is Rolls Royce. They people, they are working uniquely on three spool configuration; and if you look at carefully, my HP diameter, HP compressor diameter that's what is lower, okay, and my number of stages are also lower, okay. So, this fan that will be rotating at the low speed, my intermediate pressure spool configuration, that's what is rotating at medium speed and my HP spool that will be rotating at the high speed.

Now, this is what is representing the most recent trend, that's what is called geared turbofan engine. If you compare, here if you look at, my HP compressor stages are less, okay. You can realize the reason is, this is what is rotating at the high-speed, okay. Same way if you look at, my LP compresses stages are also lower, that is also rotating at the high speed. Now, in between, so we are having this gearbox.

So, this gearbox let my fan to rotate at low speed. So, that's what will be improving my thrust generation capacity, my pressure rising capacity. You can understand the larger diameter, the more chances the formation of shock near the tip region; mainly for your entry at the fan, okay. So, this is what we need to realize. So, now, using the fundamentals what all we are discussing, say… using your fundamental equation by increasing your peripheral speed, you are able to increase your per stage pressure ratio, you are able to reduce your number of stages, okay.

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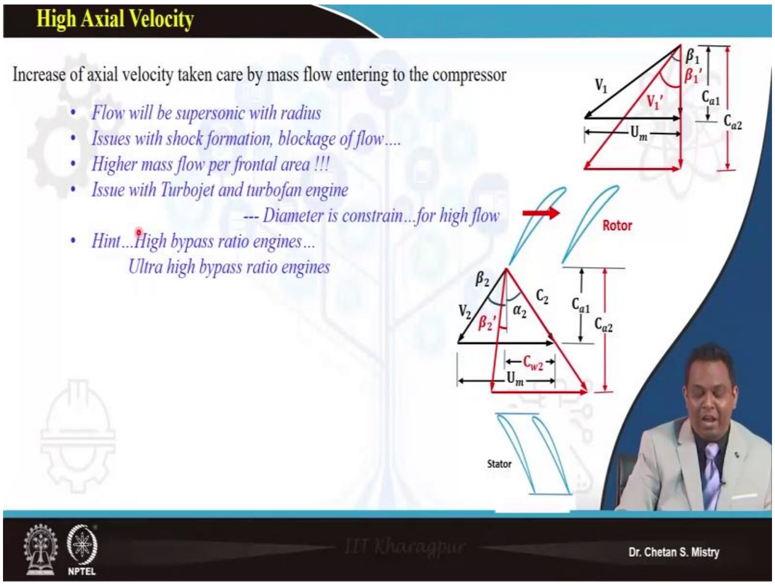

Now, let me move to the next. Say next option what we are having, it is increase your axial velocity. So here in this case, if I look at, say… this is what is say my original velocity triangle, let me increase my axial velocity. If my peripheral speed, that's what is say same. I will be having my V_1, you can see V_1' dash, that's what is my relative velocity component that will be coming to be large, okay.

Same way, if I will be putting, say… at the exit, I will be having my axial velocity to be large. If my peripheral speed is same, I will be having this kind of configuration. Now, here also, if you look at carefully, this is what is representing my β_1', that's what is lower than β_1. And here, this is what is β_2', that's what is lower than that to my β_2.

Now, again, the situation is same as what we have discussed for your high-speed configuration. What happens? You will be having your flow to be supersonic or it will go in transonic region at particular radius. Issue that's what is same, you will be having formation of shock. It will give the blockage to your flow and that's what is, reducing your efficiency, okay.

Now, the question is like these all other limitations, and as I told people they try to come out from these difficulties of formation of shock. Now, the challenge, that's what is come is how do we increase our axial velocity? Just realize, this axial velocity, that's what is a responsible parameter for my mass flow rate, okay.

So, what it says? In order to have your axial velocity to be large, you need higher mass flow rate per frontal area, okay. Frontal area, in the sense, my air that will be sucked from my front side or from my, say… for high bypass or low bypass ratio engine, my air that will be sucked from the entry. Even for turbojet also it will be entering from your entry case or say my diffusing passage, okay.

Now, what happens, this is what is creating the trouble. Suppose if I am talking about the turbo jet engine and turbofan engine, we are having some constraints in sense of diameter, okay. And this diameter, that is what will be going to be large. So, many times when I am talking about, say my application to aero engines, okay, especially for military configuration, where my diameter it is a constraint; when my diameter is a constraint, I cannot go with increasing my frontal area, okay. So, a logic of increasing your axial velocity with limited frontal area, that's what is tricky, okay.

Now, what hint it is giving? You are having option for high bypass ratio engine, that's what we are using for our commercial aircraft. You can go with high bypass ratio or very high bypass ratio kind of engine, that's what is called ultra high bypass ratio engines. So, by 2025, we will be having future engines, they are ultra high bypass ratio engine.

So, you can understand, people with maturity of technology with understanding, fundamental understanding of what all we are learning they are being implemented, okay. So, you know, you need to be very thorough with all these aspects. Once you are having your fundamentals to be clear, you can think in an innovative way just find the solution with the problem, okay.

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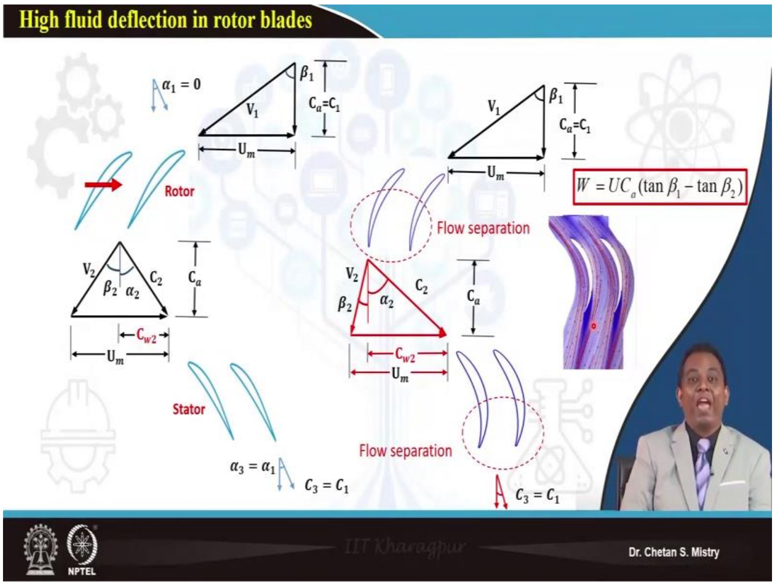

Now, let me go with say our next configuration, what it says, like high fluid deflection in the rotor blade. So, here if you look at, this is what is suppose if I say, I am having my original blade, okay. Now, it says I need to have higher deflection. So, I have modified my airfoil in order to accommodate $\Delta\beta$, that's what is $\beta_1 - \beta_2$. If you look at, this case, I will be having my airfoils that will be changing like this. It says it is cambered airfoil, highly cambered airfoil compared to these airfoils, okay. So, this is what is say my rotor blade, okay.

So, if I will be putting my say… velocity triangle here. This is what is my configuration, that's what is say my entry velocity, it say… my V_1 and my angle is β_1. Now, what happens, say at the exit my relative velocity component that will be going to be lower. Just look at, if you compare side by side, you will realize, say… here what V_2 we are getting (low cambered airfoil) and what V_2 we are getting (high cambered airfoil), this velocity at the exit of my rotor, that's what is coming to be lower, okay.

And, my β_2 angle also is coming to be lower. It says I am having my $\Delta\beta$ to be large, okay. Now, what happens, what flow that's what will be coming out at one side it is reducing my relative velocity, but on the other side, it is increasing my absolute velocity. Now, the challenge that what has come is in sense of your next component, that's what we say is absolute velocity component, that's what is entering in my stator.

So here, if I look at, I am looking for my exit, that's what is say…axial. So, you know, we will be having our stator also as highly cambered blade, okay. So, this blade, that's what is cambered blade, this blade is also cambered blade. You can say this is what is my rotor and this is what is my stator.

Now, the challenge that what has come is with your aerodynamics. What it says? We are working under adverse pressure gradient, my entry pressure is lower, my exit pressure is higher. When my flow, that's what is acting under adverse pressure gradient, we have more chances for my flow to get separated.

So, you know, like, if I consider, this is what is a region where I will be having more chances for my flow separation to happen. It will not limited only with the rotor, it may happen that you will be having your flow separation, that's what will be happening in my stator, okay. So, one of the simulation what we have done in this, like this is what is representing my streamlines, and you can clearly see for the stator we are having the flow separation, that's what has happened from the stator blade.

So, you know, going with larger $\Delta\beta$, that's what is very challenging. So, the trend, that's what is going on, it is to make per stage pressure rise to be large using this kind of configuration by changing my $\Delta\beta$ to be large, this is what is very challenging. People they are working on this aspect. At IIT Kharagpur also, we have explored designing high pressure ratio low speed compressor. So, this is what is one of the simulation what we have done.

So, you can see this is what is the problem, it may happen that your flow separation that will be happening from your suction surface, many chances it may happen, you will be having your flow separation that will be happening even from your pressure surface, okay. So, to achieve high pressure ratio, per stage pressure ratio for axial flow compressor, that’s what is always very challenging part, okay.

And, today we have discussed about different possibilities. One of the possibility we have discussed, that’s what is in sense of increasing your peripheral speed. Second option we have opted, that’s what is by increasing your axial velocity. And third option we have discussed, that’s what is by increasing your flow deflection or making your blade to be highly twisted or highly cambered.

Thank you very much for your attention! we will be moving forward in the next lecture, this all will be giving you very much fundamental idea what we say in sense of design of axial flow compressor. With all these fundamentals, if you will be moving ahead, you will be having detailed maturity, what we say in sense of design.

So, design of axial flow compressor always is very challenging. And that is the reason why a whole lot of research and development activity, that’s what is going on throughout the world for the development and design of this axial flow compressors. Thank you. Thank you very much!