Aerodynamic Design of Axial Flow Compressors & Fans
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Lecture – 23
Cascade Aerodynamics

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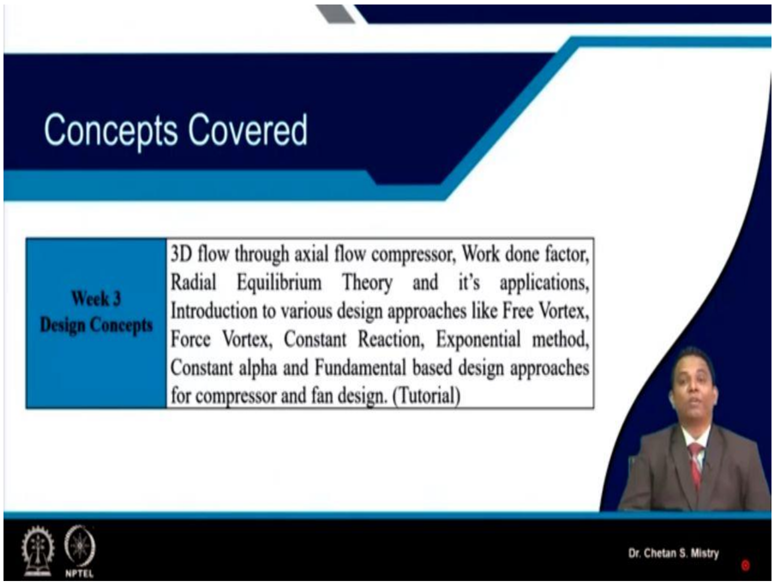

Hello, and welcome to lecture 23rd. In last module, we started discussing about the three-dimensional flow through axial flow compressor. We realize, the growth of boundary layer from both the walls along with the adverse pressure gradient, that's what is we are imposing because of axial flow compressor. In combination with the tip leakage flow, that's what is making our flow to be highly three-dimensional near the end wall region. And when we say, we are having highly three-dimensional flow in that region, we need to take care of what all changes it is making.

Mainly we have realized, the axial velocity near these end walls that's what is going to change. And in order to do the compensation during our design purpose, we have introduced the parameter; that's what we have defined as a work done factor. We have discussed, there is something called blockage factor, that's what different industry they are adopting for their initial stage of design. Then we started discussing about high the flow three dimensionality; that's what is happening within our passage.

And we realized, because of presence of our adverse pressure gradient, we have the safe change that's what is at the entry and at the exit of my stage or say number of stages. If that's what is your case, we will be having our flow passage to be having three-dimensional shape; it will not be parallel wall, but it will be inclined wall. One more parameter we realized, that's what is the presence of centripetal action because of our rotation. We also have realized, our blades, that's what is having twist and that twist is because of change of radius; we can say at the entry and at the exit, we will be having our blade angles to be different.

And that's what is giving the three-dimensionality to my flow within the blade passage. And after that, we started deriving the fundamental equation that is called radial equilibrium equation. Now, based on our radial equilibrium equation, we re-write vortex energy equation and that's what we realized that's what we are using for analyzing our flow through axial flow compressor. These fundamental equations can be applicable to any kind of turbo machinery. Now, here in this case, after deriving that, we have done certain assumptions.

The assumptions are… we have considered our stagnation enthalpy to be constant throughout the span, we have assumed our axial velocity to be constant throughout the span, and we have derived with C_w into r; that's what is giving the free vortex formation, that's what is happening and with that we say as a free vortex low.

If we are having all these three conditions to be satisfied, we can say our radial equilibrium it is satisfied with. Then, after we started discussing about what all are the alternative compared to a free vortex design; because what we realize, when we are adopting our free vortex design concept, our blade that will be having greater twist.

At hub, we are having larger $\Delta\beta$; and near the tip, it will be having comparatively low $\Delta\beta$. And that is the reason why it is giving high twist to my blade. And because of our aerodynamic constraint, because of our manufacturing constraint, we have come up or say… the researchers, they have come up with some other adaption, different methods. And those methods we have discussed as forced vortex, constant reaction method, exponential method; we have discussed about constant α_2 method. We also have discussed our fundamental methods.

And there we have checked whether our radial equilibrium, that's what is satisfied or not. If it is not satisfying, say for the case of constant reaction design, my radial equilibrium it is not satisfied. And it says there maybe possibility that what we are expecting in sense of pressure rise or efficiency that may not be achieved, because my radial equilibrium it is not getting satisfied there.

Now, with all this background, you can realize, now we are able to do calculation for throughout the span what is happening. Let me recall again, say we have discussed, our blades; say stator blade and rotor blade, they are made up of number of airfoils.

These number of airfoils, they are being placed throughout my span, it may be 10, 20, maybe hundreds of airfoils; and all these airfoils they are performing particular work, okay. And that’s what is responsible for what we are talking in sense of getting pressure rise at the outlet. Now, after learning all these aspects, so we can understand, we have realized, we have done our calculation for what will be the variation of my flow angle at the entry, and what will be the variation of my flow angle at the exit. And we have taken care of parameter called degree of reaction. Now, after doing this, very important aspects that will be coming into the picture; that’s what is the selection of our airfoils.

And in order to understand how do we select this airfoil, the fundamentals of cascade mechanics, that’s what is very important. So, now in session-4, we will be discussing about the cascade aerodynamics, okay.

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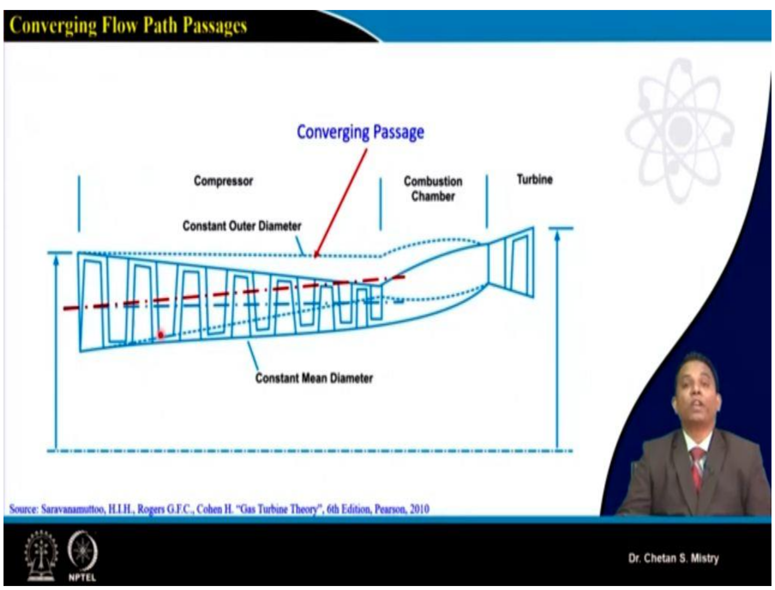

Now, let us move here. So, if we recall, we were discussing, say if we consider this is what is my entry of the compressor; we can say, this is what is my exit of the compressor; and that exit, that’s what is connected with my combustion chamber. So, if you look at this full line, that’s what is representing my flow passage as some passage, and we know, this passage shape, that’s what is converging passage shape. Let us recall again, what we have discussed, for my fluid flow, we need to have our continuity need to be satisfied at the entry and at the exit.

Suppose, if I consider I am having my density ρ_1, my area is A_1 and my axial velocity is C_a. At the exit, I will be having my density say ρ_2, we will be having our area A_2, and my axial velocity we are assuming to be constant. If that's what is your case, we realized for axial flow compressor, downstream of my stage we will be having rise of pressure. We can say, when my pressure is rising, my density also will be increasing. If that's what is your case, and if I consider my axial velocity to be constant, my exit area will be coming say lower. So, compared to my inlet area, my outlet area will be coming to lower; and that's what is giving my converging passage.

Now, let me consider, I do not want to put my flow track; this is what is called flow track, where I am arranging all my stages for axial flow compressor. Let me tell you again, there is a specific reason behind using number of blades and number of stages. The purpose for adopting number of stages, that's what is we are having limitation in sense of aerodynamics. When we are increasing our pressure rise, per stage pressure rise to be large, there maybe chances for the flow to get separated from the blade; and that's what we have defined as a stall. And that is the reason why my per stage pressure rise, that's what is limited.

If my per stage pressure rise it is limited, means in order to achieve required pressure rise, I need to go with the number of stages, okay. So, here in place of having this kind of passage, let me put my passage like this. So, if we are considering say original passage, that's what we can say my mean diameter, that's what is coming to be constant. So, it says constant mean diameter passage. And here if you look at this dotted line, I say that's what is say… constant tip diameter kind of track, okay. So, we will be focusing on how this passage shape or how this flow track or flow passage, we will be deciding.

Because, that's what is very important when we are doing our design for axial flow compressor; because we do not know which stage exactly we are designing or we are asked to design for. Maybe I will be designing first stage, maybe I will be designing last stage. But to have this idea, we need to have certain dimensions; and those dimensions, that's what is based on my flow track dimension, okay.

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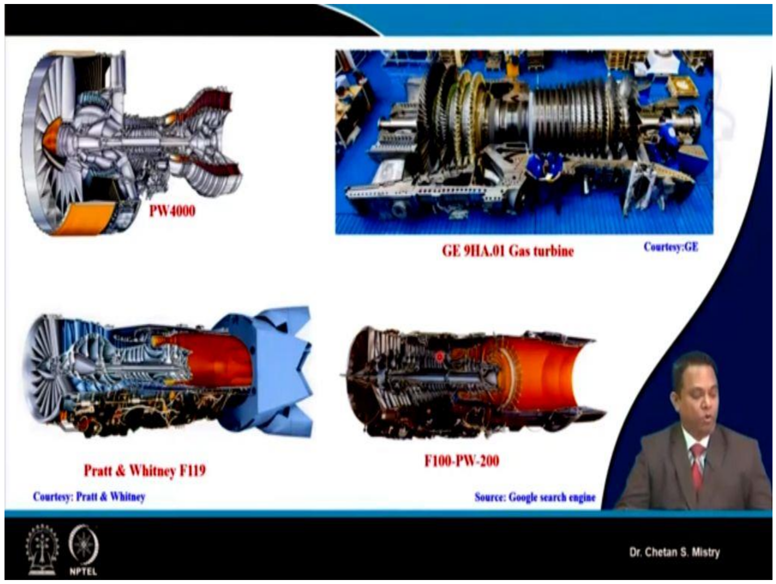

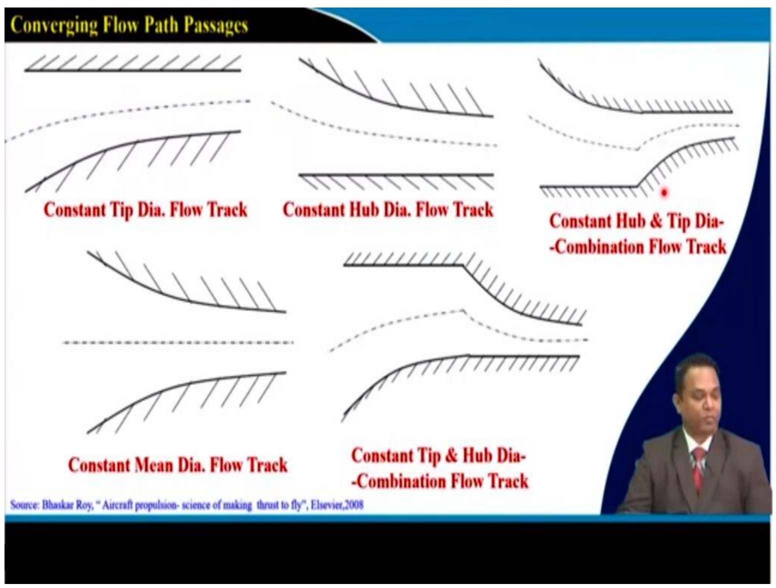

So, let us look at this. So, if you look at here, this is what is Pratt and Whitney 4000 engine; you can say, we are having say… large size fan. Then, it will be followed by this is what is my booster stage, or we can say as LP spool or say LP compressor. Downside here, this is what we can say as HP compressor. Here we are having combustion chamber, HP turbine and LP turbine. So, we know this is what is my 2-spool configuration. Now, my HP turbine, that's what will be rotating at the high speed; and that's what my compressor – HP compressor that will be rotating at a high speed.

Now, we have understood our fundamental equation for Euler. And what it says? My work done or say my pressure rising capacity of the compressor, that's what is depend on my peripheral speed;

or we can say it depends on my rotational speed. If I consider I am having higher rotational speed, you can understand, we need to go with say… slightly smaller diameter. So, that is the reason why my HP spool, if you look at, compared to my other spool dimensions, say compared to this diameter, this diameter that's what is coming to be lower. Now, the question will come, what is the reason why we are having this diameter to be larger?

Again, this LP compressor, it is operating at low pressure; but it may be generating high pressure, that maybe designed for high pressure ratio. So, in order to achieve that high-pressure ratio, we need to have our peripheral speed to be larger. And, we know our LP spool, that's what will be rotating at low speed, maybe 3000 rpm, maybe 6000 rpm. If that's what is your case, in order to increase your peripheral speed, your diameter need to be larger, okay. So, now you can realize, it is not because this kind of flow track that's what is giving good aesthetic look; just understand the technicality in this design.

There is a specific reason behind selection of this diameter, just realize that part. Very important part here, that's what is say… this is what is called interconnecting duct. So, you can say, my low-pressure compressor, that's what is connected with the high-pressure compressor using this interconnecting duct, okay. So, that is also very important component and that is also coming in the scope for design by the designers of axial flow compressors, okay. So, you can realize, say, I need to have sudden change of my diameter, from larger diameter to say… smaller diameters, that's what is one thing, what flow that will be coming out from my LP spool that may be having some angularity, it may be having some whirl component.

So, before it will enter into HP turbine, HP compressor, we need to have, you know, flow to be managed systematically; and this is what is my inter compressor duct, okay. Now, this is what is my land-based power plant; you can realize for land-based power plant, they are having that shape that's what is coming to be different. Here if you look at, this diameter is coming to be large, this diameter is small, that's what we are expecting. But, at the same time, here in this case, if you look at, this is what is having different shape compared to these two configurations. Let us move here.

This is what is say… Pratt and Whitney F119, okay; that's what is low bypass ratio engine. So, here for this case, if you look at, I am having curvilinear shape here at the entry near the hub. And if we look at here carefully, say… for first two stages, I am having constant tip configuration, and then it will be moving downside. This is my bypass duct. If you look at my HP compressor, you can realize, that's what is having some kind of configuration, where my tip diameter is coming to be constant, okay. Now, here this is if you look at, this is what is say Pratt and Whitney 200. For that also, if you look carefully, you can see for this case, we are having our tip diameter, that's what is almost constant; and if you realize here, my hub diameter they have maintained to be constant for HP spool.

So, if you recall, if you try to understand what all shapes you are getting for our flow track; we will see, we are having some configuration that's what is say…constant tip diameter flow track. We can have constant hub diameter flow track, we can have constant mean diameter flow track. And you know for high spool or we can say for high bypass ratio and low bypass ratio engines, we maybe having combination of constant tip and hub diameter; we can have constant hub and tip kind of configuration. So, now you can understand, we are having different kind of flow track configurations which are possible.

So, we will be discussing what all are the advantages or where we will be using this kind of flow tracks. They are having special purpose, special reason behind the selection of these flow tracks.

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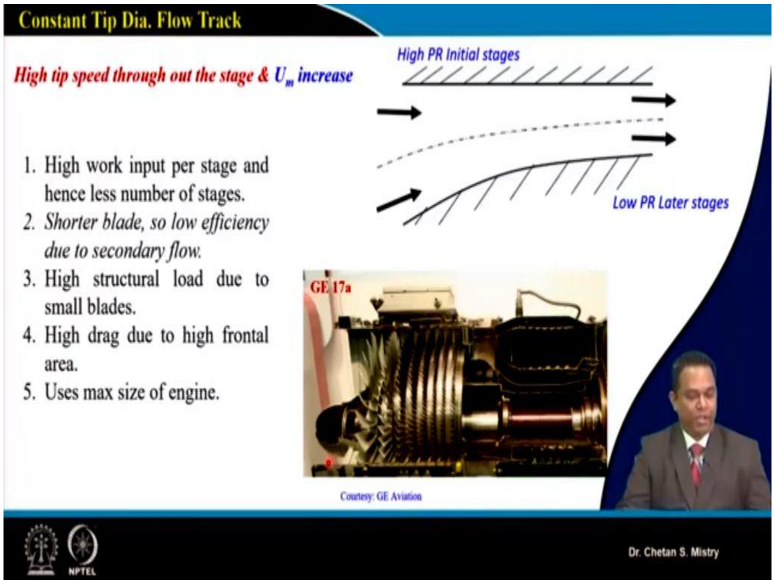

Now, if you look at here, say, this is what is you can see constant tip diameter kind of configuration, okay. So, at the entry what we are expecting? We are expecting our high-pressure ratio for the initial stage, and later on we are not expecting much pressure ratio; that's what is a design strategy, okay. And here in this case, if you look at my tip diameter, that's what is constant; and if you look at carefully, my mean diameter, that's what is increasing progressively, okay. So, you can say it is… you will be getting higher tip speed; at the same time my U_{mean} that means my peripheral speed at the mean station that is also increasing, okay.

So, here if you look at, this is GE 17a; for that if you look at, this is what is my constant tip diameter kind of configuration. Here at the entry, you are having larger area; at the exit, you will be having lower area, okay. Now, what will happen? If this is what is the possibility, what we know, if I will be having higher peripheral speed or high tip speed, it will give me high per stage pressure rise, okay. And if I will be getting high per stage pressure rise, that means, the number of stages required in order to achieve particular pressure rise, that will be reduced, okay. So, this is what we can say… its advantage in sense; because per stage pressure rise we are achieving to be higher.

It says in the later stage, if you look at, say… suppose say for these blades; if you look at in later stage, I will be having smaller blade height; that's what is aerodynamic constraint. We have discussed earlier also; we will be having our growth of boundary layer from casing; we will be having growth of boundary layer from our hub. And that may be possible in the later stages, whole my blade or maybe quarter of my blade or half of my blade that will be covered with this blockage.

And that's what will not give what pressure rise we are expecting, because of formation of losses there. That's what we are defining as say secondary losses and that will lead to reduce the efficiency for that particular stage, okay. Suppose, if I will be considering this as a configuration to be fitted in my aircraft, we can say… that's what is giving higher drag; because it is having higher frontal area, okay. And it is using maximum diameter of my engine. Now, let me tell you, say… when we are discussing, we are looking for compact engine, we are looking for lightweight engine or; when we are looking for engine to be fitted in the fuselage, okay, for my military applications, there, you know, we are expecting our per stage pressure rise to be large.

Under that condition, this is what will be coming into the picture. One more thing, we are not major concern of efficiency and when we are talking about military application. So, you can understand, this is what is giving good configuration in sense when we are doing our design for the compressor.

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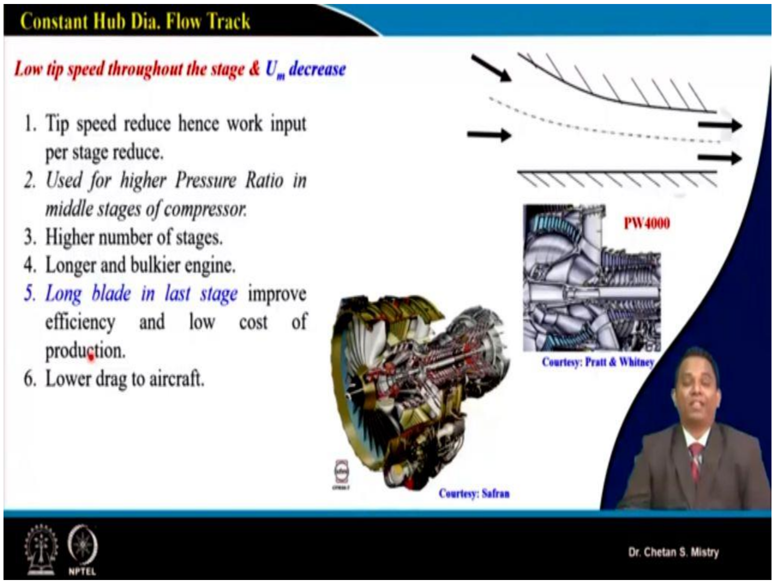

Now, suppose if we consider, say I am having constant hub diameter kind of configuration. If that's what is your case, you will be getting lower tip speed; and, you know, our mean peripheral speed, that's what is going to decrease. So, this is what is going to decrease. If this is your configuration compared to our earlier case, we can realize our tip speed, that's what is reducing, that means my per stage pressure rise what I will be getting, that is lower, okay. And when we are considering this kind of configuration, okay, so we will be having say… this configuration, that's what is required more number of stages.

So, it is suggested, that's what we can use for high pressure ratio in middle stage of compressors; this kind of configuration we can plan for that. One major advantage compared to our constant tip configuration is… now we will be having say longer blade that will be coming at the exit stage. If that's what is your case, you can understand, we will be having minimum losses. When we are having these losses to be minimum, my efficiency is going to increase. So, here if you look at, this is what is a section for Pratt and Whitney 4000. And if you consider for HP configuration, they are having nearly constant hub kind of configuration.

This is a Safran CFM 56 engine; for that also, in order to have this kind of benefit; they people they have configure this HP compressor with constant hub diameter, okay. And this is what will be reducing your production cost also; and lower drag that's what is a benefit for your aircraft. So, we can understand, this is also one of the configuration which we can explore, okay. But, the limitation here is in sense of length, because my number of stages are going to be large, okay. So, for military application if you are planning for, you need to do systematic calculation for per stage pressure rise, okay.

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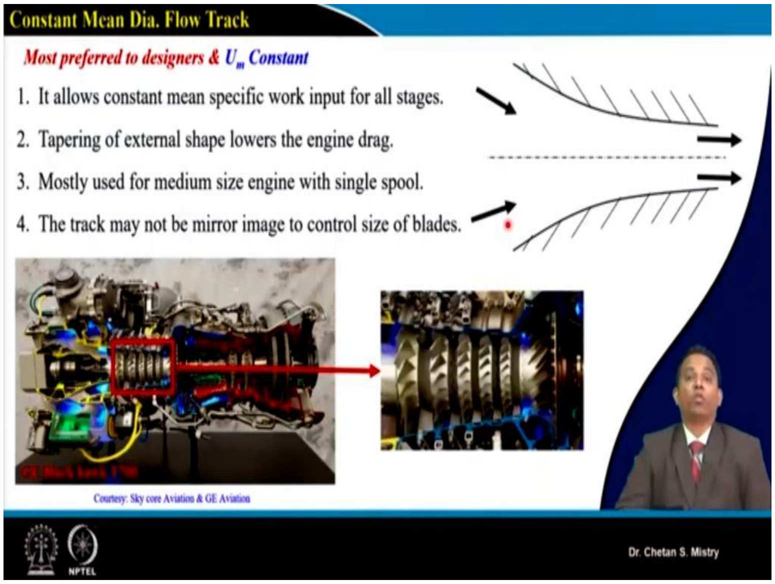

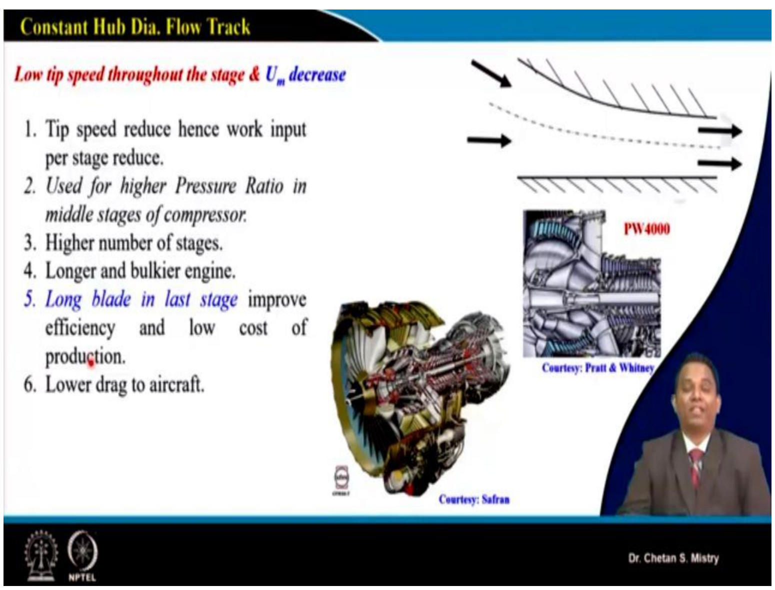

Now, this is what is a configuration in which I am having my mean diameter that's what is constant; you can see, this mean diameter it is constant, okay. And this is what people used to say it is a most preferred design to add up or to go with a constant mean diameter kind of configuration, okay. So, it says it allows constant mean specific work input for all the stages; that's what is a big benefit, okay. If you consider we are having tapering of this external surface; that's what is going to reduce the engine drag, okay. Suppose, if we consider a constant tip diameter configuration, we realized that's what was giving our drag to be more.

Here because of this tapering shape, we are having lower drag; that's what we are getting, okay. And, mostly used for medium size engine with single spool. So, here if you look at, this is what is say… turbo shaft or we can say turbo probe kind of configuration, in which, this configuration for axial flow compressor, it is considered as a constant mean diameter kind. One more thing, the track may not be the mirror image to control the size of the blade height, okay. So, if we will look at, suppose if I consider say this is what is your case; this is what is my constant mean diameter kind of configuration. You can understand in order to accommodate or in order to have proper height of my blade, they are not considering always the mirror image, okay.

So, this is what is the most promising kind of configuration what people they have explored. Now, the question will come, why do not we think of something in sense of combination of these two, maybe constant hub and constant tip diameter which say, mean configuration and that's what will be giving us benefit of both what we are looking for. Yes, so, we are having that kind of configuration.

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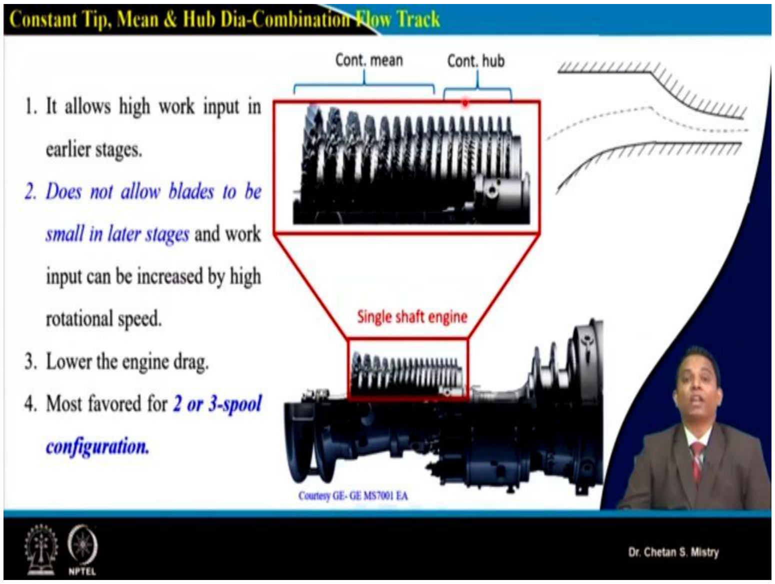

So, here if you look at, this is what is say constant tip diameter configuration and later part that's what is constant hub diameter configuration. So, it says we are able to achieve high work done for the initial stages, okay. And it does not allow what problem we are having which say a constant tip configuration is the height of my last stage blade. That's what you can get right by using constant hub diameter kind of configuration, okay. So, it says, does not allow the blade to be small in the later stage, and work input can be increased by having higher rotational speed.

So, this is what we have seen for most of our high bypass ratio engines, okay. This is what is giving lower drag that's what is of need when we are talking about the application to commercial aircraft, okay. In commercial aircraft, we are looking for the configuration which will, looking, we are looking for a specific fuel consumption to be lower. We are looking for fuel economy that is where this is of major concern, okay. And, it says, it is most preferred for 2 and 3-spool configuration. So, this is what is one of the land-based power plant; that's what was developed, designed by GE and that's what is having single spool configuration.

And if you look at the whole this single spool, it has been designed with the combination of say…constant mean diameter and constant hub diameter. So, this is also one of the possibility, okay. So, we can say, we are having different kinds of flow tracks which are possible when we are doing our design and development activity for axial flow compressor.

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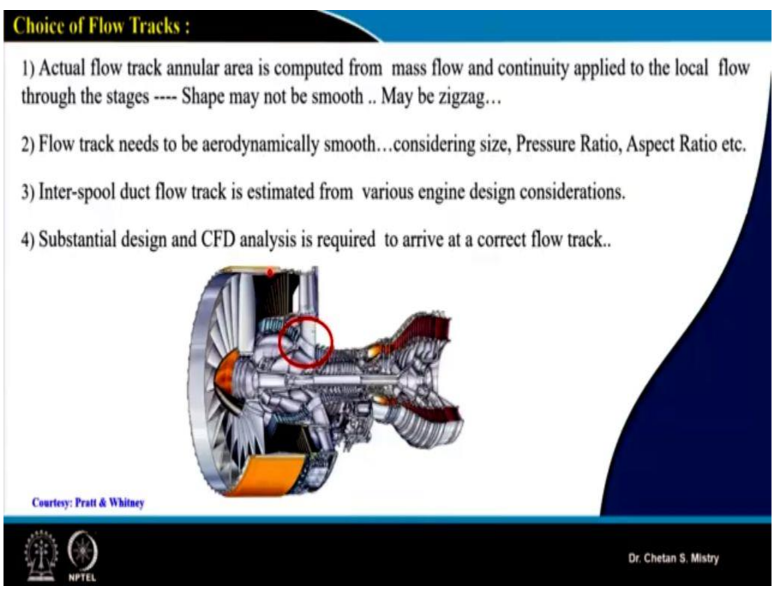

Now here, so, if we look carefully, say very first thing what we are doing when we are developing the axial flow compressor is we will be going with our cycle analysis; maybe by using your pen paper, or maybe by using say commercial tools, or maybe companies they are having their own code for doing the cycle analysis. After doing that cycle analysis, they are defining or finding with what will be the pressure ratio required for LP spool, and what will be the pressure ratio required for HP spool, okay. Now, based on pressure ratio requirement, they will be deciding with the number of stage; now, number of stage decision that's what is very important.

You can understand here, suppose if we consider this is what is say... having say pressure ratio around 20, let us see. So, you know, like for 20, we can go with say…maybe 5 stages, we can go with at 8 stages maybe, we can go with 10 stages; it is designers' choice. Again, the problem will be with the length of the engine, it may not be permitted to go with more number of stages; length of the engine, weight of the engine, number of components or number of blades required for the compressor that also will be larger. So, all these are the constraints.

So, based on that initially, systematically, total pressure ratio that's what has been decided. Then after, per stage it has been decided with. Now, per stage calculation, that's what is done, I will be having my inlet pressure, I will be getting my outlet pressure; based on the continuity, we can calculate what will be my outlet area. Now, again for the next stage; so systematically you need to do all your calculation. So, it says actual flow track annular area is computed based on mass flow and continuity applied to local flow for each stages; the shape may not come smooth.

So, you can understand, suppose if I am considering first stage, say I have assumed my pressure ratio as say… 1.4. I will be getting my exit area to be slightly different; maybe when I will be going with this next step. So, I will be getting zigzag kind of configuration. Now, we know in our aerodynamics, we are not permitting any kind of flow obstruction. That means, we need to have our flow track to be aerodynamically smooth, okay. And that's what is based on your, you know, size… overall size of my stage. When I say overall size of my stage, that's what will be coming in sense of my radius ratio; that's what is coming in sense of my aspect ratio, okay.

Then next, that's what is my pressure ratio. And what aspect ratio as we have discussed, that's what is coming into the picture. So, all these configurations together, that will be giving some kind of rough idea, a rough estimation of my flow track. Now, what happens? After that, we need to smooth out that track; that means, maybe here and there, you need to adjust your radius. So, once you are defining or you are finalized with your track, then you will be getting your numbers at the entry and exit. And then, your design for particular stage that's what will be started with; but, the design what I mean is blade design, okay.

So, do not underestimate the importance of flow track design; this is very important. So, in companies, people they are having expertise in such kind of flow track development. They have flow track engineers; their whole work it is to take care of all this configuration. Let me tell you one more point, that's what is say… this inter connecting duct or inter compressor duct; that is also equally important. As I told, my flow which will be coming out from my LP or LP compressor, that will be going into say HP compressor.

And if you consider, I will be having great variation in my radius. So, what all we have discussed in module-1 for our diffuser concept, that concept, that aerodynamics that's what will be coming into the picture. Now, in order to do all this calculation, people they are substantially using CFD analysis, okay. And then after, they will be coming up with perfect or systematic flow track, okay. So, you can understand, I cannot go with having say… experimentation at the initial stage, okay. I cannot make number of flow tracks and then after do the experimentation. So, computational tool, that's what is helping here. So, once we finalize with that, maybe later on, you can check with the experimental part, and that will be helping.

So, the aerodynamics of say axial flow compressor, it is not only limited with your blades; it is also covering this flow tracks, interconnecting ducts, okay. So, we need to be very careful when we are doing our design. So, what all you are deciding in sense of my rotational speed, in sense of my peripheral speed that means diameter, all those parameters which are very important. So, when we will be discussing in the next module, we will be discussing how exactly we will be discussing for all these aspects.

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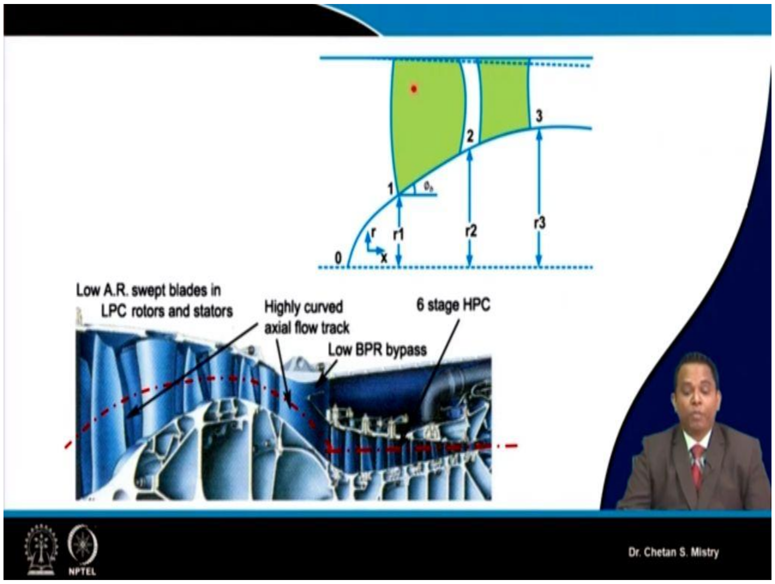

Now, here in this case, say…if you look at carefully, say this is most modern kind of configuration. So, here, if you look at, this is what is most modern low bypass ratio engine configuration. So, you can see, we are having low aspect ratio stage, say…almost three stages we are having, okay. And the track if you look at, this is what is systematically been designed with constant mean diameter kind of configuration. If you look at my say HP spool, that HP spool that is if you look carefully, that is also of constant mean diameter kind of configuration.

And as we have discussed, this is my bypass duct, okay. Here in this case, the shape of this inter compressor duct, that’s what is very important, okay. So, if you look at carefully, say… initially when you are doing your design, you will be getting your flow track like this. Then, later on as per your requirement, in order to have good aerodynamic characteristics for inter compressor duct, it may be possible that you maybe having some other kind of shape like this. So, here if you look at for last stage, that’s what is having other kind of configuration, okay. So, this is what people they are working at this moment.

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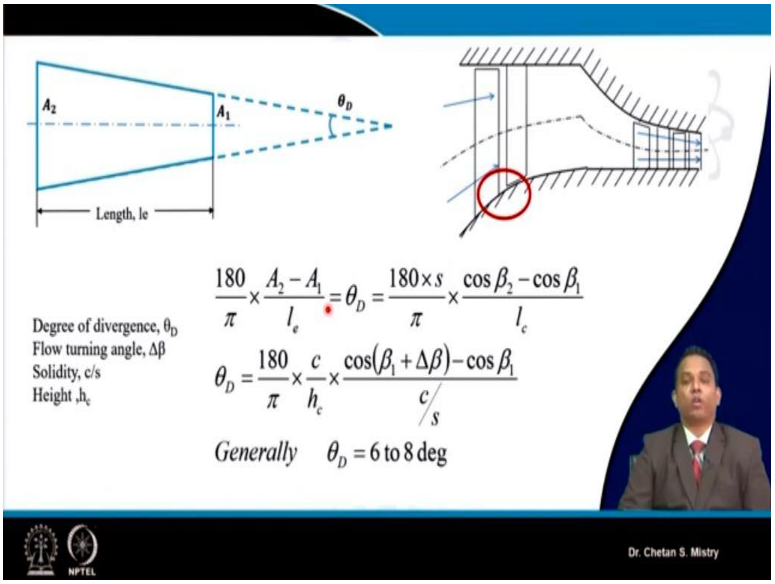

Now, you know, like the fundamentals of aerodynamics that always will remain with us. And we can have rough estimation; we can say, this is my entry area, this is my exit area, I will be having this angle as say, you know, divergence angle. This divergence angle, that's what we can calculate based on this equation.

$$\frac{180}{\pi}\times\frac{A_2-A_1}{l_e}=\theta_D=\frac{180\times s}{\pi}\times\frac{\cos\beta_2-\cos\beta_1}{l_c}$$

$$\theta_D=\frac{180}{\pi}\times\frac{c}{h_c}\times\frac{\cos(\beta_1+\Delta\beta)-\cos\beta_1}{c/s}$$

Now, let us look at here, suppose if we consider, this is what is say high bypass ratio engine kind of configuration. Here, I will be having my great turning, that's what is happening. But, for small elemental area if you look at, that's what is satisfying what angle we are discussing.

So, it says my angle, that need to be in the range of 6° to 10°, 6° to 8°; that's what is a most preferred angle, okay. Now, here in this case, we have discussed about all different kinds of configuration what we are using for say our axial flow compressor. So, I am sure, this is what will give some gleams, small initial idea. We are moving more towards now aerodynamic design of compressors, where the fundamentals of all these aspects are of great importance. So, thank you, thank you very much for your attention! Thank you!