Introduction to Airbreathing Propolusion

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Lecture - 54
Axial Compressor (Contd.,)

So let us continue the discussion on the design of axial flow compressor and we are looking at individual components and they are different components wise calculations, how to obtain different individual parameter like we have seen how we calculate the different stages, flow angles and all this.

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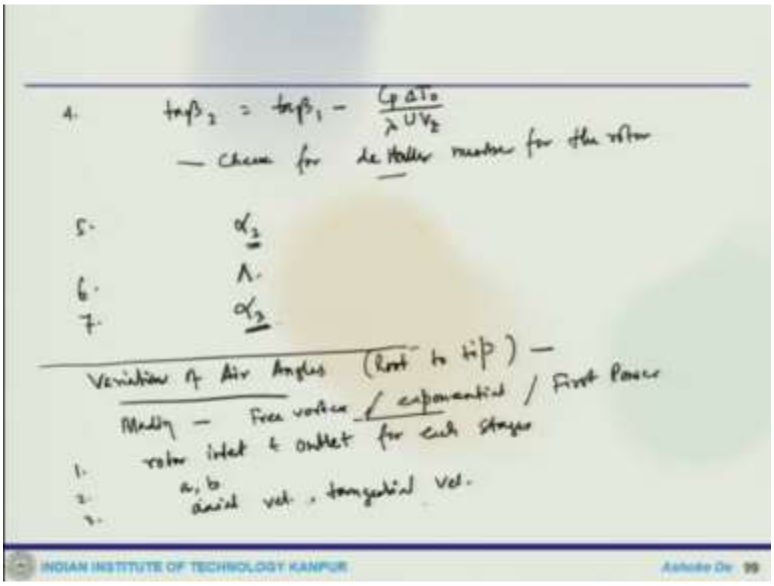

Now we will look at the next set of calculations like we go to like variation of for example air angles from so we look at variations of air angles. So that we have already seen but, this one is from, this would be root to tip and this is based on the blading that we have decided so which could be? So the blading could be any of these types like free vortex design or it could be exponential or it could be first power.

So, any of these blading parameters will dictate that so there are 3 methods that estimate this kind of variation of air properties in the radial direction from blade hub to tip. So like we calculate the dimensions at the rotor inlet and outlet of for each stages then we calculate the values of constants like a, b and all these. Then third we already have discussed about this table with the different blading parameters.

And so we can calculate the axial velocity, tangential velocity so all these component we can find out. Now to calculate the dimension upstream and downstream, the rotor stages 1 and 2 under dimensional stage 3.

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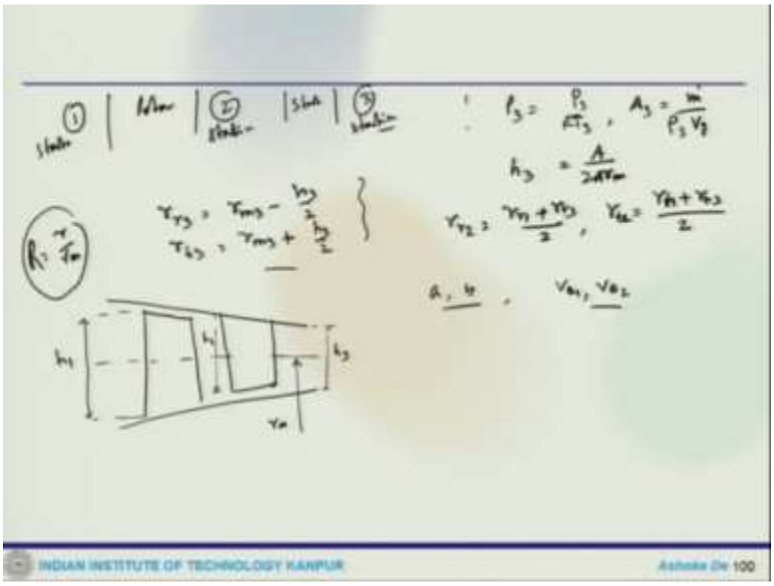

So we typically follow the continuity equation of the mass flow rate equation. So for example at row 3, so for rotor, let us say for rotor up streaming stage that is station 1, station 2 and then you have stator and that is the station 3. So now how we calculate? we get

$$\rho_3 = \frac{p_3}{RT_3}$$

where

$$A_3 = \frac{\dot{m}}{\rho_3 V_z}$$

So we now calculate the blade height there which would be

$$h_3 = \frac{A_3}{2\pi r_m}$$

Now, if the compressor is designed with constant mean radius, then the root and tip radius can be calculated very easily like

$$r_{r3} = r_{m3} - \frac{h_3}{2}$$

And

$$r_{t3} = r_{m3} + \frac{h_3}{2}$$

So this corresponding hub and tip radius at the rotor outlet are the mean value of those. So we get

$$r_{r2} = \frac{r_{r1} + r_{r3}}{2}$$

And

$$r_{t2} = \frac{r_{t1} + r_{t3}}{2}$$

So it still remains to calculate the corresponding non-dimensional radius, like the

$$R = \frac{r}{r_m}$$

so at the root tip at stages 1 and 2.

And then after calculating the constant A and B, and we can calculate $V_{\theta 1}$, $V_{\theta 2}$ so which are already. So this what we talk about this mean? You can think about like, you have a section cross section like this and this is what the mean section and that goes like this, and then that goes like this. So, if you talk about this is sort of h_1, this is h_2, this is r_m and this is h_3. So this is how it, now once we get a and b from there we get $V_{\theta 1}$, $V_{\theta 2}$ and these are already calculated. Now the axial velocity is also can be calculated using the information so that is how we do that.

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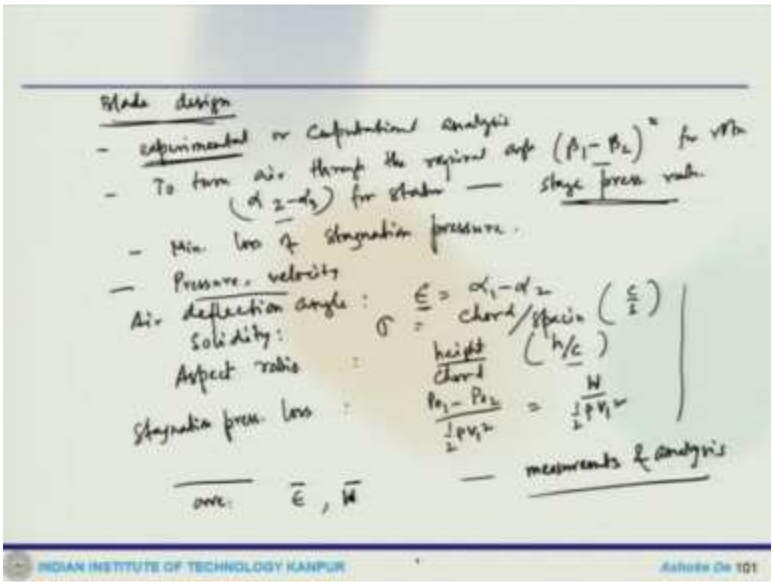

Now, we move to another one aspect is the blade design. So blade design is another important parameter. So it depends on what could be the aerofoil shape. So the design of the selections from the available aerofoil series. So this can be performed so that essentially you need either the experimental or computational analysis to decide upon the section. So the objective is to obtain an information on the effect of the different blade geometries on airflow angle, pressure loss and the energy.

So just to do that one can set it up a experimental rig or the cascade, internal and then get a lot of measurements. So, what it can satisfy that it can to turn air through the required angles like $\beta_1 - \beta_2$, So for rotor and $\alpha_2 - \alpha_3$ for stator to maximize the stage pressure ratio. So these angles are varied so that the; maximize of the stage pressure ratio can be obtained.

Now, to achieve the diffusion process with optimum efficiency or with the other words minimum loss of the stagnation. So, minimum loss of stagnation pressure. So typically the experiments are performed in the cascade, wind tunnel or this has a very well equipped facility where this kind of rig can be tested and the experiments can be conducted. And during that experiments, typical measurements like pressure then velocity.

So these are already obtained and then what it is calculate the r factor a deflection air deflection angle which will be epsilon let us say $\alpha_1 - \alpha_2$. Then we can take the solidity which is sigma chord by spacing that means (c/s) that means chord by pitch. Then aspect ratio which is height by chord that means (h/c), and then stagnation pressure loss. So, which is

$$\frac{p_{01} - p_{02}}{\frac{1}{2}\rho V_1^2} = \frac{W}{\frac{1}{2}\rho V_1^2}$$

So one can do some sort of an averaging and get some mean data of this and mean deflection angle like average epsilon bar, W bar, these kinds of things. So this could be measured and plotted and these are plotted for different values off. Now done deflection angles once you get then these are actually collectively I mean all these measurements are put together collectively.

And then through some data or calculating procedure, the deviation and angle can be obtained. So these are basically what one can say that a detailed measurements and analysis would allow the proper blade designed to help, because there could be some correlation between these deflection angle with this chord by spacing (c/s) ratio or and all these would play an important role in getting those data.

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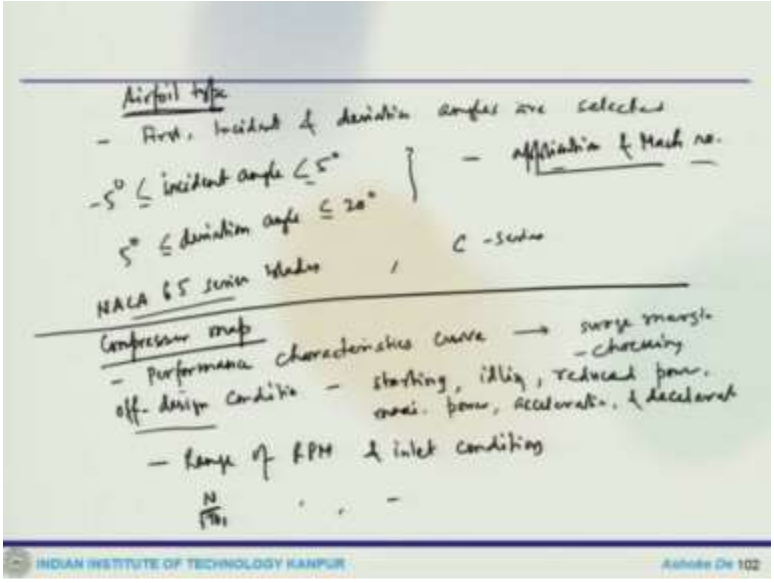

So, once while talking about the blade design, one of the important aspects of the airfoil type, because these are very, very important because after the radial distribution of the air angles and velocities which are determined, so the bladings can be designed. And for that, the proper selection of the air foil is needed. Now first the incident and the deviation angle are selected. So, first incident and deviation and angles are selected.

So that the slope of the aerofoil of the mean line camber line at the leading and trailing edge can be established. So for minimum losses, incident angle, typically the incident angle, the range of incident angle could be somewhere $\pm$5 degree and a devious angle which could be in a range of let us say in order to 5 to 10 degrees, so that much deviation. So then the mean line shape and thickness are selected once the mean line shape and thickness are selected to achieve the desired aerofoil loading.

So the pressure increase in a achieved by the diffusion process, then the amount of diffusion is monitored. So the nature and type of blading depends on the application and so this is one of the important aspect application and Mach number. That means whether it is subsonic range, high subsonic range, transonic range or supersonic range. So that will determine this because once you go to transonic or supersonic range there would be shockwaves.

And that will have some loading on the frontal stages. So these things already we have looked at it. And the typical series which is used is the NACA 65 series blades. These are typically used and that is what then there are another series from this is American and then there is a

British series called the C series. So these are also used in the compressor, now after that aerofoil selection.

So you need to have the data for or rather the important part is the compressor map. So the compressor map or other performance characteristics curve. So this will provide you surge margin, choking. So these are very, very important parameter. So any compressor which is designed that has to perform smoothly without going into stall or later on surge. So we will have some off design conditions like typically they are I mean perform fine when that is in the operating condition

But in the off design conditions, there will be problem like off design conditions which is like starting or engine starting, idling, reduced power, maximum power, acceleration and deceleration. So these are some of the off design conditions so compressor has to operate satisfactorily over a wide range of RPM. So, range of RPM and inlet conditions so this is also another condition that this has to do that.

But since the annulus area and compressor blading are choosing to satisfy the design point conditions only it may possible like other conditions like off design conditions, they may not perform properly. So comparing maps for excellence, centrifugal compressor, one can notice that for a fixed value of $\frac{N}{\sqrt{T_{01}}}$ the range of muscularity is narrower in axial compressor than the centrifugal one.

And also at high rotational speed, the lines become very steep and ultimate I mean, maybe vertical. And then you have surge point, which occurs before the constant speed curves reach a maximum value and stall surge characteristics are similar to overall characteristics at much lower pressure ratio. And for the axial flow compressor since the axial velocity is maintained constant annulus area is inversely proportional to a density, thus the annulus area of the compressor decreases. So these are the; from front to rear stages.

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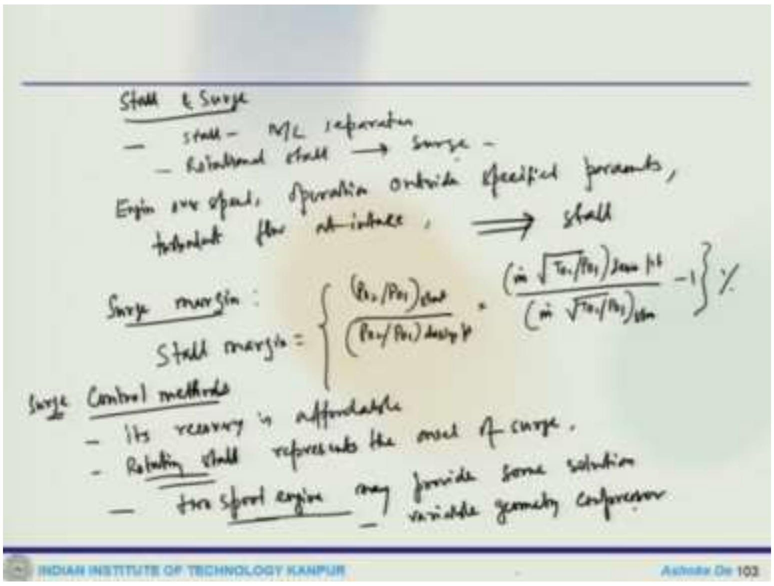

So just to accommodate all the other characteristics. Then we have stall and surge these are another some of the other factors. So stall is such a situation when the airflow through a single or multi stages of the compressor surge a situation which lead to due to the stall or in the stall. So basically stall means boundary layer separates or flow separates. So you start having all sorts of a different flow dynamics in the blade passages.

Or in the rotor passages then in the stall becomes more and more dominant and the it leads to rotational stall this can lead to surge. So which; will be another unsteady condition or unstable condition of the compressor. So there are certain things like engine over speed or operation outside specified parameters sudden like turbulent flow at intake or some other damage performance of the engine so these can all lead to stall.

So then there are rotating stall and surge phenomenon also these are quite severe problem in the axial flow compressor, and that not only has direct impact on the material or the loading, but also degrade the performance of the compressor. So these are the issues. And now one can find out some of these surge margins that we have already looked at from the compressor chord that where does the surge margin actually lies.

And then mathematically one can find out these surge margins. So this is very similar to the factor of safety in mechanical system design, which is called stall margin would be

$$stall\ margin = \left\{ \frac{(p_{02}/p_{01})_{stall}}{(p_{02}/p_{01})_{design}} * \frac{\left(\dot{m}\sqrt{T_{01}/p_{01}}\right)_{design}}{\left(\dot{m}\sqrt{T_{01}/p_{01}}\right)_{stall}} - 1 \right\} \%$$

So these are some of the ways one can represent these things so surge occurs in operating engine.

It occurs at distance stoppage of the air flow through the compressor. So these are the things which could have all sorts of problems with these things. Now, then how do we control? Control methods so this is for rather surge control methods. This is sort of an unavoidable, but it is recovery is affordable. So at the same time, we are seeing that surge is unaffordable. It is recovery is affordable since rotating stall represents the onset of surge.

If one can avoid the stall then obviously the rotating stall can be avoided and subsequently the surge but or rather, however this is an impossible task due to different operating conditions for the compressor which are housed or other installed in aero engine, powering airplane, any particular mission but for compressor in industrial power plant, different conditions are found during starting, idling, acceleration, decelerations.

So, probably things can be bit controlled there, but also another thing that can come into that, the designer they propose different methods to control this I mean, like they propose to control the surge in a different ways. Like they said that multi-spool that 2 spool engine may provide some solution, like instead of having a single pool engine, if 2 spool engine is there. So these are the designer choice that can avoid some sort of, and, or reduce the possibility of having surge and all these.

So each spool and consequently, the compressor rotors are different speed. So moreover they develop the variable geometry and also the variable geometry compressor. This can also provide a solution to control some of these methods, so just to overcome the surge and all these.

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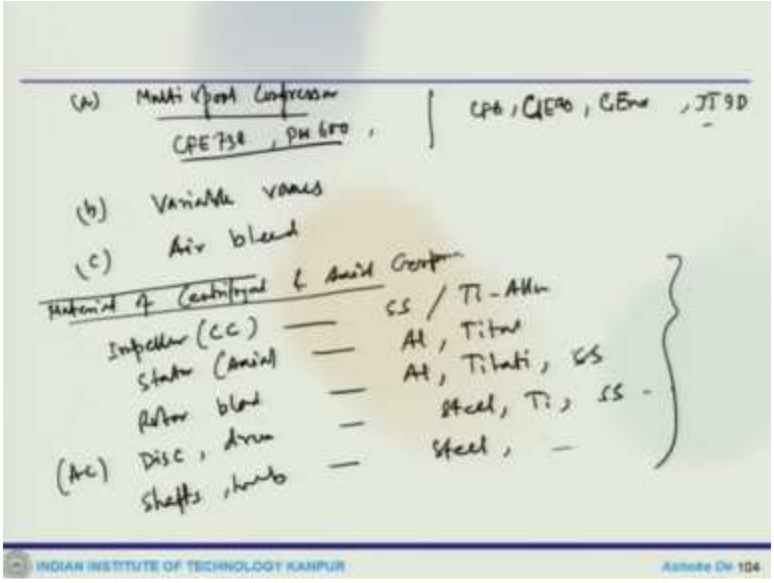

So solutions, which are typically used a is the multi-spool compressor. So that is reduction in compressor speed from design value will cause an increase of the incident in first stage and decrease of the incident in the last stage. So that probably could be a choice. And this kind of, there are plenty of examples like there, like a general electric engine CFE 738, Pratt and Whitney PW 600.

Then also there are high by-pass ratios two spool turbofan engine, like a CF6 and GE90 then GEnx pattern would need JT9D like that BW 4000. So there are plenty of turbofan engine. Or second option is that using variable vanes. So that could be another way one can control or third is that you some air bleed. So these are the things for one can use just to avoid or rather control the surge phenomenal.

So air bleed is something that what one can do that bleeding here downstream of the stall stages and will allow something. Now the; last part which is important in the material of this centrifugal and axial compressor. So the thing is that compressors all have low density and high strength material. So these are very, very important just to know different materials like one can have different components.

Like one is impeller, for centrifugal compressors CC centrifugal compressor. These are used at stainless steel. Now stator vane this is for axial compressor so these are used. So this could be titanium alloy also titanium alloy, and this could be aluminum titanium based alloy. Then you have rotor blades. So this could be also aluminum, titanium, stainless steel and some other.

Then you have disc drum, these are also for axial compressor. This could be steel titanium, stainless steel and so on. And then you have these mechanicals parts like shafts and hub which could be steel or other materials. So these are some of the materials that one can use for this, a material perspective of the centrifugal and axial flow compressor. And these are important parameters.

Because when you do the design and as you see there are full thermodynamical design or then you have all this materialistic conditions of the materialistic property, because all these blades, rotor blades, stator blades they are exposed to a lot of different kind of stresses and loading. So that pretty much concludes the axial flow compressor. And we will stop the discussion here and continue our discussion in the next lecture.