Introduction to Airbreathing Propulsion
Prof. Ashoke De
Department of Aerospace Engineering
Indian Institute of Technology – Kanpur

Lecture – 48
Axial Compressor (Contd.)

Okay, so we are continuing the discussion on the axial flow compressor so we started the stage dynamics now we have also looked at the how the pressure increases.

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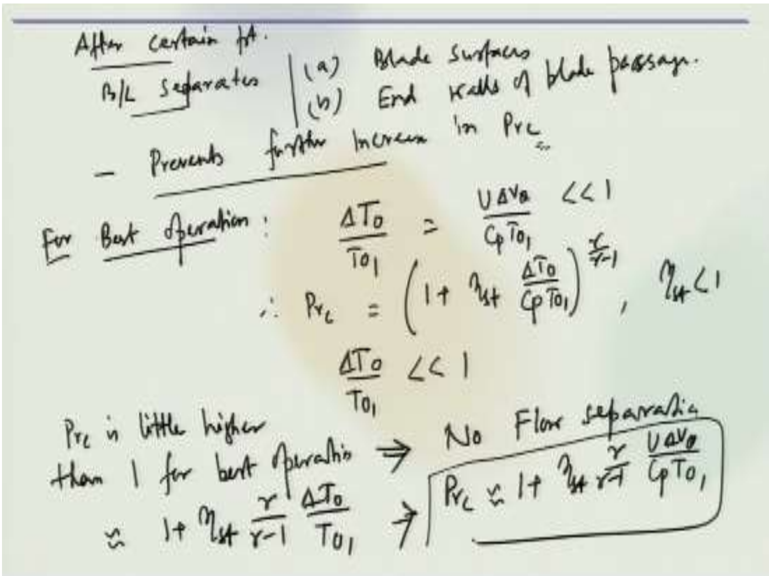

Now we will continue from here what actually the best possible operation that we are talking about. So, this is what we have already looked at that what can stop the pressure rise. So best operation or best possible operation for or rather for best operation one can think about

$$\frac{\Delta T_0}{T_{01}} = \frac{U \Delta V_\theta}{C_p T_{01}} \ll 1$$

So P_{rc} would be

$$p_{rc} = \left(1 + \eta_{st} \frac{U \Delta V_\theta}{C_p T_{01}}\right)^{\frac{\gamma}{\gamma-1}}$$

Since $\eta_{st} < 1$, $\frac{\Delta T_0}{T_{01}} \ll 1$ and P_{rc} is little higher than one for best operation so there will be so P_{rc} is little higher than one for best operation so which will lead to no flow separation. So that equivalent to

$$p_{rc} = 1 + \eta_{st} \frac{\gamma}{\gamma - 1} \frac{\Delta T_0}{T_{01}}$$

$$p_{rc} = 1 + \eta_{st}\frac{\gamma}{\gamma - 1}\frac{U\Delta V_\theta}{C_p T_{01}}$$

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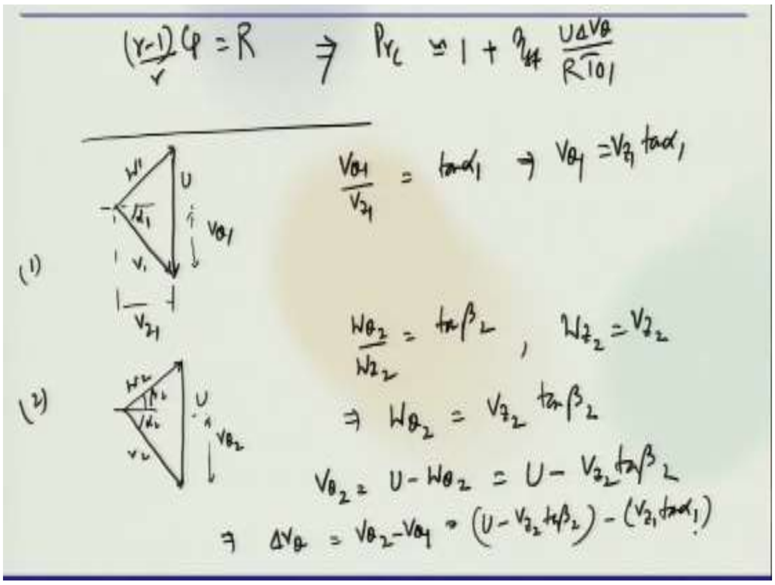

Now further simplification what it gives

$$\frac{\gamma - 1}{\gamma} C_p = R$$

so if we put it back we will get

$$p_{rc} = 1 + \eta_{st}\frac{U\Delta V_\theta}{RT_{01}}$$

So for these are design point analysis at off design conditions. Now at off design condition one can look at what happen so let us consider the same blade passage with same velocity triangle. So that means if we consider the same velocity triangle.

So this is V_1 this is V_{z1}, W_1 so this is U so this component is $V_{\theta 1}$ so we have α_1 so $V_{\theta 1}$ by now this is at station 1. So

$$\frac{V_{\theta 1}}{V_{z1}} = \tan\alpha_1$$

that means

$$V_{\theta 1} = V_{z1}\tan\alpha_1$$

Now similarly at 2 we have the triangle so this is U again, this is W_2 β_2, α_2, V_2 and this is your $V_{\theta 2}$. So what we get

$$\frac{W_{\theta 2}}{W_{z2}} = \tan\beta_2$$

$$W_{\theta 2} = W_{z2} \tan \beta_2$$

Now

$$V_{\theta 2} = U - W_{\theta 2}$$

so which one can write

$$V_{\theta 2} = U - V_{z2} \tan \beta_2$$

so that means

$$\Delta V_\theta = V_{\theta 2} - V_{\theta 1} = (U - V_{z2} \tan \beta_2) - (V_{z1} \tan \alpha_1)$$

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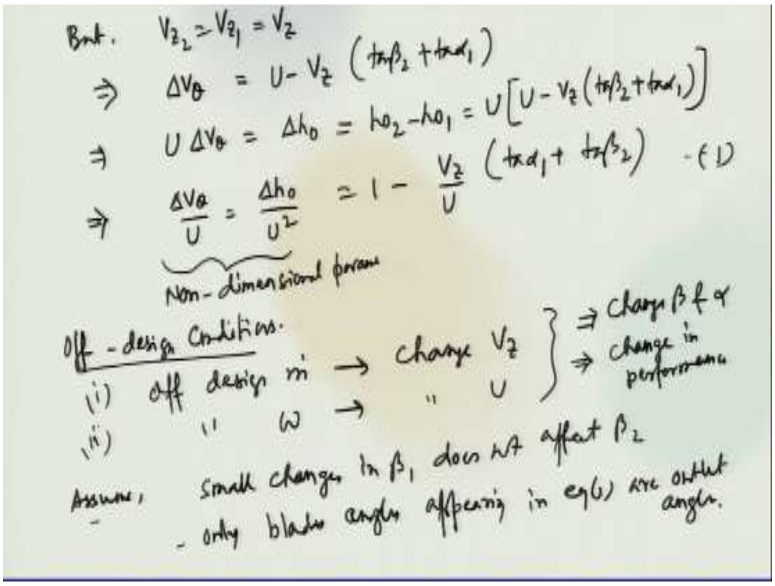

But we have V_{z2} is V_{z1} so flow remains axial so that let us have

$$U\Delta V_\theta = \Delta h_0 = h_{02} - h_{01} = U[U - V_z(\tan \beta_2 + \tan \alpha_1)]$$

So we get

$$\frac{\Delta V_\theta}{U} = \frac{\Delta h_0}{U^2} = 1 - \frac{V_z}{U}(\tan \beta_2 + \tan \alpha_1)$$

so that let us say so this is the non dimensional parameter. Now what will happen at off design condition is that now off design m dot which means there is a change in V_z or if there is a off design rotational speed there is a change in U.

No matter what it is it is actually changes β and α so the performance effect so the change in performance. Now there is an effect of the change of m dot on design condition. So one can do that let us assume small changes in β_1 does not affect β_2. So which means the blade provides strong enough flow at the outlet angle is independent of the inlet angle and only blades angles appearing in equation 1 are outlet angles.

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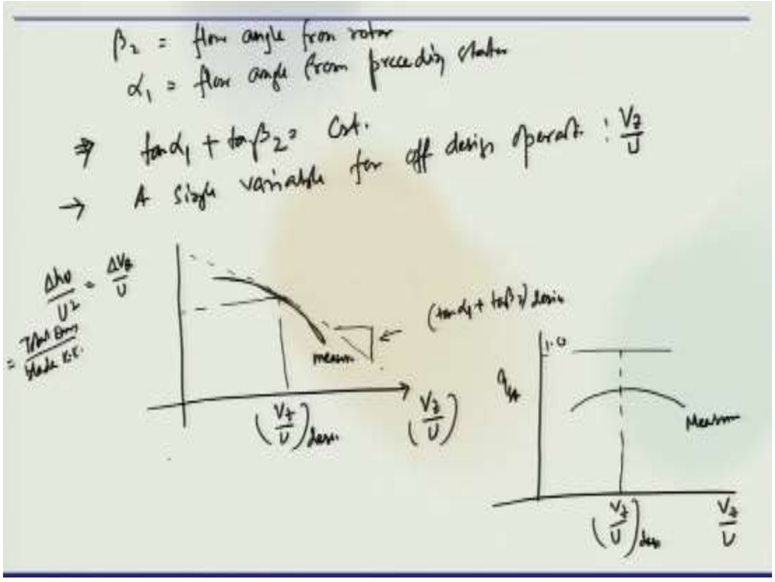

So which means β_2 would be the flow angle from rotor α_1 is the flow angle from preceding stator. So in total $(\tan\alpha_1 + \tan\beta_2)$ is constant. So which assuming this while the entire result of departure from design condition are concentrated in a single variable $\frac{V_z}{U}$. So what we get a single variable for off design operation that is $\frac{V_z}{U}$. Now we can plot this parameters like this is how we can plot that $\frac{\Delta h_0}{U^2}$.

This is $\frac{V_z}{U}$ and $\frac{\Delta h_0}{U^2}$ is the ratio of basically total energy so this is total energy divided by blade kinetic energy which is $\frac{\Delta V_\theta}{U}$. So this plot would look like an curve like in this so this is your $(\tan\alpha_1 + \tan\beta_2)$ at design and this is measured and this guy $\frac{V_z}{U}$ at design. Similarly, you can plot η_{st} this is which will look like that and this is $\frac{V_z}{U}$ again this is $\frac{V_z}{U}$ design and this is measured.

So from this one the curve 1 so there is a small departure from the design conditions of $\frac{\Delta h_0}{U^2}$ it looked like quite closely with the ideal value and little effect on the measured stage efficiency and the second point is that larger departure from the design case will have large differences between actual and ideal work. So this is due to possible boundary layer separation. So one can look at this parameter by analyzing like β_1 which could be uniquely determined by $\frac{V_z}{U}$ and other parameters. So with that one can look at that.

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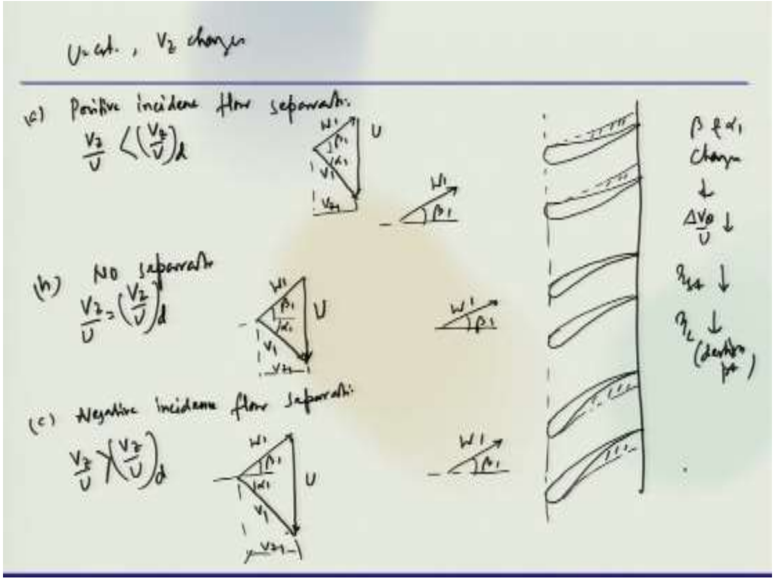

So let us see when we have like U is constant and V_z changes. So we can have a situation where you have this blade so separation took place so this is what you can think about this is positive incidence flow separation where

$$\frac{V_z}{U} < \frac{V_z}{U}_{design}$$

So the triangle is like this so W_1, β_1, α_1, V_1 and this is V_{z1} and W_1 this is the β_1. So second situation could be no separation so where my

$$\frac{V_z}{U} = \frac{V_z}{U}_{design}$$

that means the passage would look nicely behaved.

So this is what would happen and the velocity triangle also looks nice so this is $V_1, W_1, U, \beta_1, \alpha_1$ so we have V_{z1} or we can have negative incidence flow separation. So which means it could be like this so separate from here so the flow separate. So again this remain similar. So here the

$$\frac{V_z}{U} > \frac{V_z}{U}_{design}$$

This is $V_1, W_1, U, \beta_1, \alpha_1, V_{z1}$. So qualitatively the results would have been same if you had been varied while V_z was held constant.

Now the main point is that for sufficiently large departure for from $\frac{V_z}{U}_{design}$ the boundary layer separates. When that happens blades are no longer effective in controlling the flow so β and α_1 that changes. So that causing the drop in $\frac{\Delta V_\theta}{U}$. So also you have η_{st} that decreases so flow separation results in increased viscous losses. So obviously the compressor efficiency also η_c also drops below the design point or that design value.

Now this kind of flow separation that may induce unsteadiness in the flow causing the compressor surge. So far what we have been looking at all these at the single stage, but in the multi stage also.

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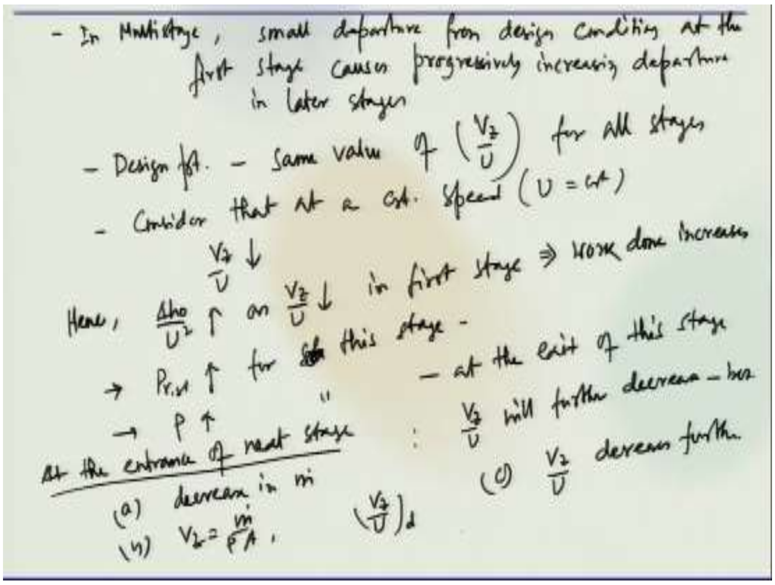

Now in multi stage case small departure from design condition at the first stage causes progressively increasing departure in later stages. So now if you consider a multi stage compressor having same characteristics for each stage. So your design point is same value of $\frac{V_z}{U}$ for all stages. Now consider that at a constant speed which is U is constant. Now the flow rate into the compressor is slightly reduced so what will happen $\frac{V_z}{U}$ which drops.

Hence, $\frac{\Delta h_0}{U^2}$ this goes up as $\frac{V_z}{U}$ drops down in first stage so work done increases. Now stage pressure rise $P_{r,st}$ also increases for this stage. So, density also increases for this stage at the exit of this particular stage. Now when you look at the entrance of next stage what will happen? So $\frac{V_z}{U}$ will further decrease because number a decrease in $\dot{m}$ dot, number b since

$$V_z = \frac{\dot{m}}{\rho A}$$

extra increase in P at the exit of the first stage. So this enhances the departure from $\frac{V_z}{U}$ design number c $\frac{V_z}{U}$ decreases further. So more work will be done causing more rise in pressure in next stage and further increase in ρ.

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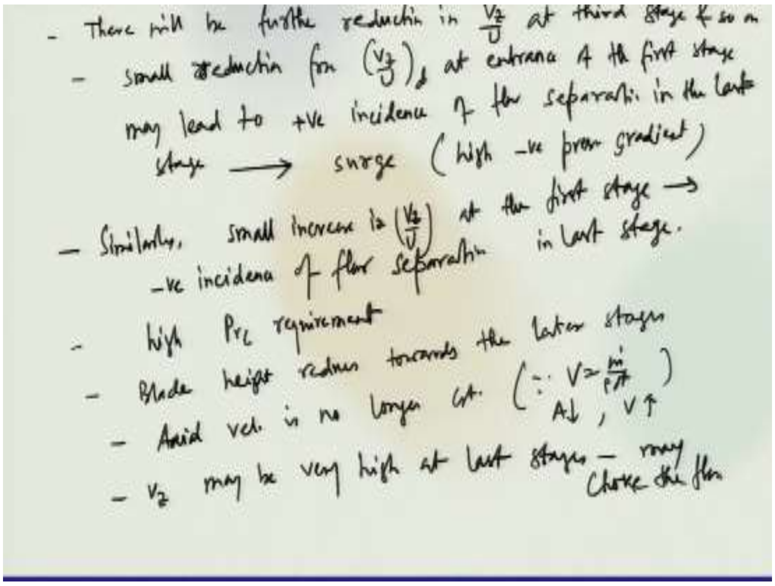

So it is clear that there will be further reduction in $\frac{V_z}{U}$ at third stage and so on. So as we keep on going stage after stage that is going to happen. So, thus the small reduction from $\frac{V_z}{U}$ design at entrance of the first stage may lead to the positive incidence of flow separation in the last stage. So small reduction from $\frac{V_z}{U}$ design at entrance of the first stage may lead to positive incidence of flow separation in the last stage.

So this is where compressor goes to surge so there is a high negative pressure gradient. Similarly, a small increase in $\frac{V_z}{U}$ at the first stage which may cause negative incidence of flow separation in last stage. So it is possible with front stages working normally the end stages would be forced to very small high value of $\frac{V_z}{U}$ at the end stages which may produce negative pressure rise.

So in that case this is what may possible happen first stage or the beginning front stages are working fine, but the later stages may not behave properly and this is where the compressor is no longer act as a compressor it will act as a throttle. So the problem of stage mismatch is more severe during engine starting especially for high P_{rc} requirement. So this is the time where you requires high.

So there is a large variation in density of the air across the stages and the stages are designed with reducing blade height to accommodate this density variation and that is why the blade height reduces towards the later stages. Now during starting there is no variation in density and remains low until the compressor is working properly. So axial velocity is no longer constant because these $\frac{\dot{m}}{\rho A}$, A reduces so V goes up. So V_z can be very high at the last stages and may choke the flow and V_z may be very high at last stages and may choke the flow.

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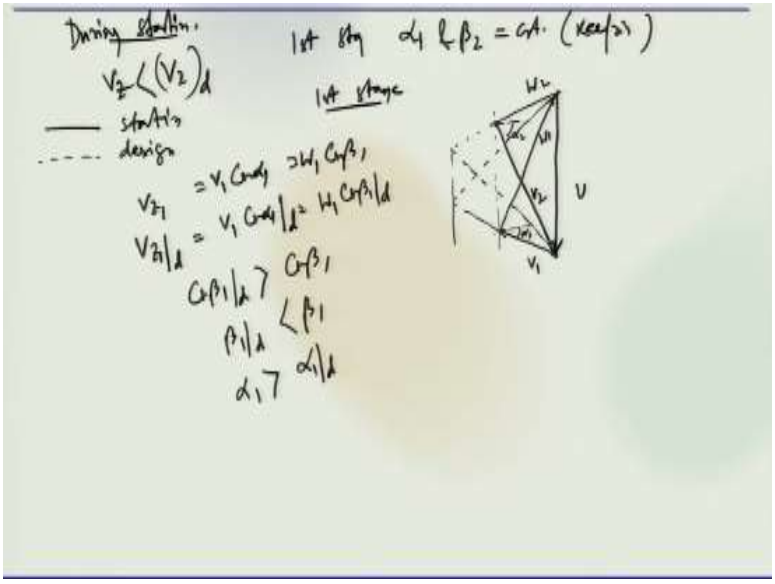

So what happens that during starting

$$V_z < V_{z,design}$$

Now at the first stage alpha and β_2 are kept constant so these are keeping it constant. Now we can draw the velocity diagram. So these are for starting and these are for design. So first stage so this is how it goes so that $U, W_2, V_2, W_1, V_1, \alpha_1, \alpha_2$. Now this could be design point this is so this is what it first stage it goes like so where

$$V_{z1} = V_1 \cos \alpha_1 = W_1 \cos \beta_1$$

$$V_{z1_{design}} = V_1 \cos \alpha_{1design} = W_1 \cos \beta_{1design}$$

So this is what happened at the first stage and similarly at the last stage also we can look at this, but we can see these things what happens in the conditions. So when you go to the second stage similarly we can draw the velocity diagram and look at design conditions of the angles. We will stop it here and continue the discussion in the subsequent lecture.