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

Lecture – 47
Axial Compressor

Okay, so let us continue with the discussion on compressor. So what we have so far discussed about the centrifugal compressor and we have also discussed about the characteristics and how to represent them and we discussed about the operating region or rather the zone where it should be safely operational like the stall margin, surge margin and the choking point. Now with that discussion we will now move to the discussion of the axial flow compressor.

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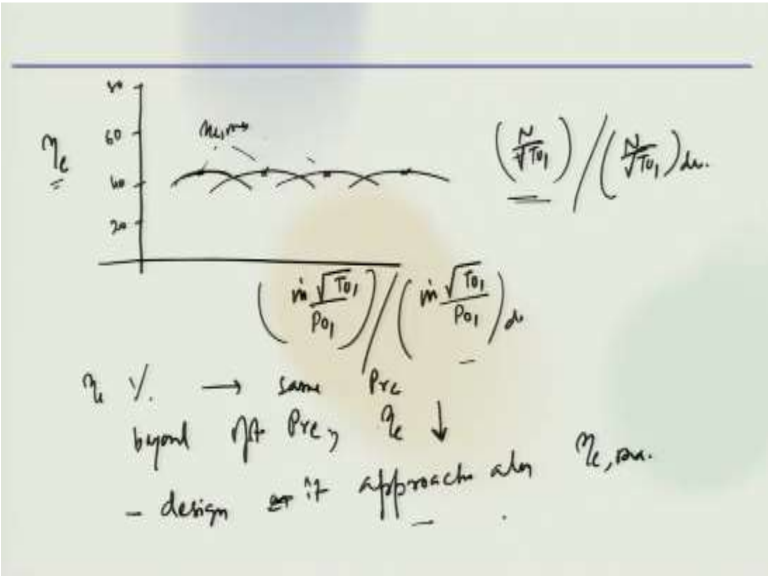

So this is where we have actually stopped.

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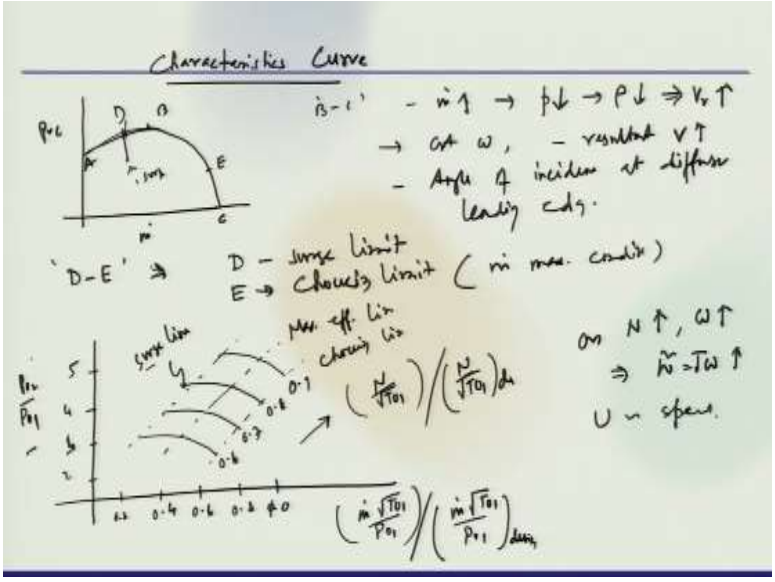

If you recall these are the two characteristics curve. One is the pressure rise versus non dimensional mass flow rate and the other one is the efficiency versus non dimensional mass flow rate. So these are the performance characteristics curve and this is what we have done.

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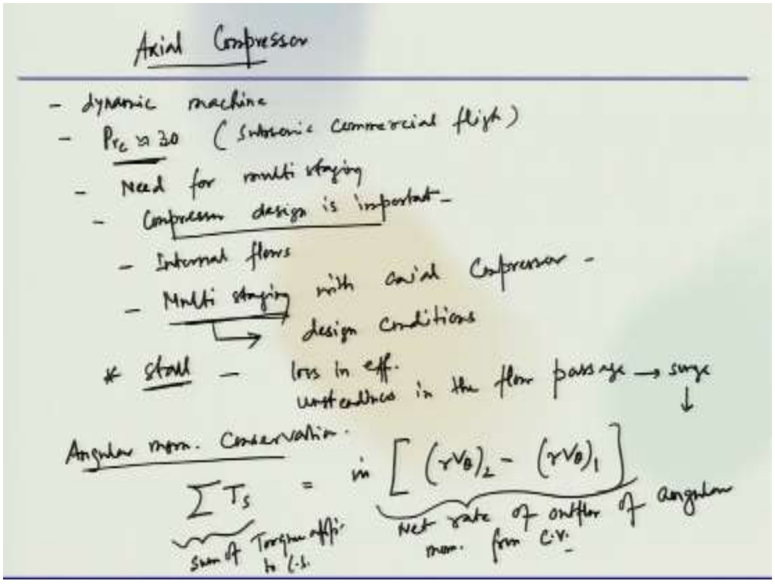

So now we will move to the axial compressor. So this is what now we will look at it. Now axial flow compressor has a slightly different again it is also dynamic machine obviously this is also rotating machine and obviously you get the fluid to be compressed to a desired and here also there is a change in fluid momentum so there is a pressure change. So, overall engine performance strongly depends on the pressure rise and the efficiency.

Now typically when the P_{rc} is low somewhere around 30 which is sort of subsonic commercial flight. So in that case this kind of pressure rise is not possible to obtain through centrifugal compressor because using one single straight centrifugal compressor this kind of pressure rise cannot be obtained. So you need multi staging and multi staging is not so need for multi staging.

And with centrifugal compressor this is not very handy or rather is not a feasible solution. So one can go for now another thing what is important is that compressor also contributes lot of the weight to the machine so this is a massive part. So in order to maintain the low weight of the engine the compressor has to be designed properly that means the compressor design is important.

So that engine weight is also kept low and the compressor is designed so efficient weight that it can give you proper pressure rise and these are all sort of an internal flows. So these are having different challenges and one can easily go multi staging with axial compressor. So that is quite easy and that is what is preferred in any modern days gas turbine engine. So when you talk about multi staging these obviously put some restriction.

So there are design conditions or rather the design constants are quite severe. So main parameter that restricts the operation of a axial through compressor is stall. So this is one of the important issue and stall as we have already discussed this is a separation of the boundary layer in blade passage due to positive pressure gradient in the flow direction. So it can lead to severe loss in efficiency.

Also it can have unsteadiness in the flow passage so which may lead to surge also and when there is a surge this could be really detrimental for the structural conditions of the blade and the material. So now again in this case also we will use that for the angular momentum conservation. So that is what this is also valid for axial compressor too and what we have already known that summation of the sum of the torque applied to the control surface would be

$$\sum T_s = \dot{m}[(rV_\theta)_2 - (rV_\theta)_1]$$

So this is sum of torque and these are net rate of outflow of angular momentum from control volume this is applied to control surface angular momentum control volume. So mostly the torque which is applied by the shaft connecting the turbine and the compressor so small negative torque contribution due to tangential component the frictional forces which are negligible.

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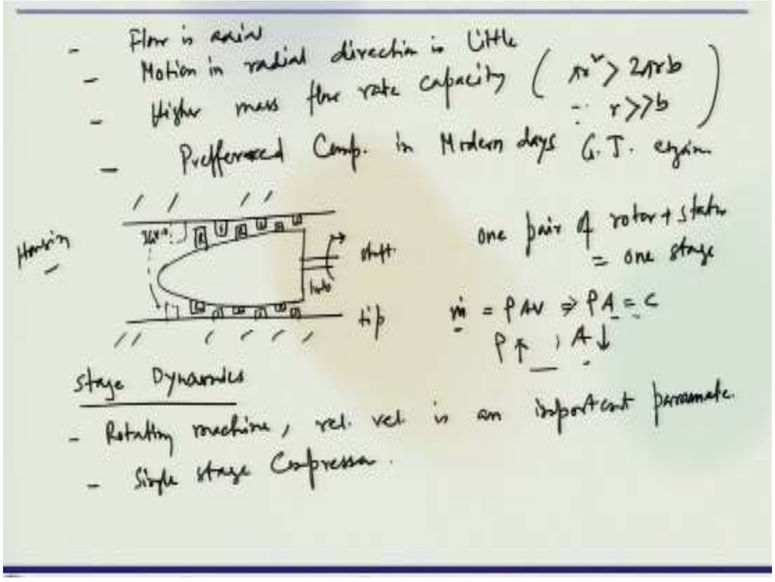

And the flow is predominantly axial. So motion in radial direction is little not very much and also axial flow compressor has much greater mass flow rate capacity than the centrifugal one. The reason is so it is a higher mass flow rate capacity compared to centrifugal one because

$$\pi r^2 > 2\pi r b$$

since r is higher than the b. So and that is why this is one of the preferred compressor in modern days' gas turbine engine.

So you can simply look at and it should be like this is how it is connected so one can have that like this is tip, this should be hub, this is shaft now one can have then rotor, stator, rotor, stator, rotor, stator. Similarly, one can have this rotor, stator, rotor, stator, rotor, stator and these are the inlet guide vane or IGV and this is complete housing that is an schematic of the rare.

So, you have one pair of rotor plus stator is one single stage. So stator is mounting or rather mounted on the housing stationary so stator is stationary component. So typically average axial velocity is same at all stages. So this is done by design so what happens the mass flow rate is constant so which means if ρ goes up A has to come down. So that is why across all stages if the mass flow rate is constant and velocity is also pretty much same this remains constant.

So when the ρ goes up because the pressure rise is increasing area decreases so that is what you have blade height reduces in the direction of the flow and the inlet vanes are allowed to smooth entry of the flow to the system. So, first we will look at the stage dynamics. So what we will look at is that so here also it is an rotating machine so relative velocity is an important parameter or component.

So we now consider a single stage compressor so just for the simplify the analysis or to keep the analysis simple we just consider single stage and then imagine that a cylinder surface are the mean radius is unwrapped.

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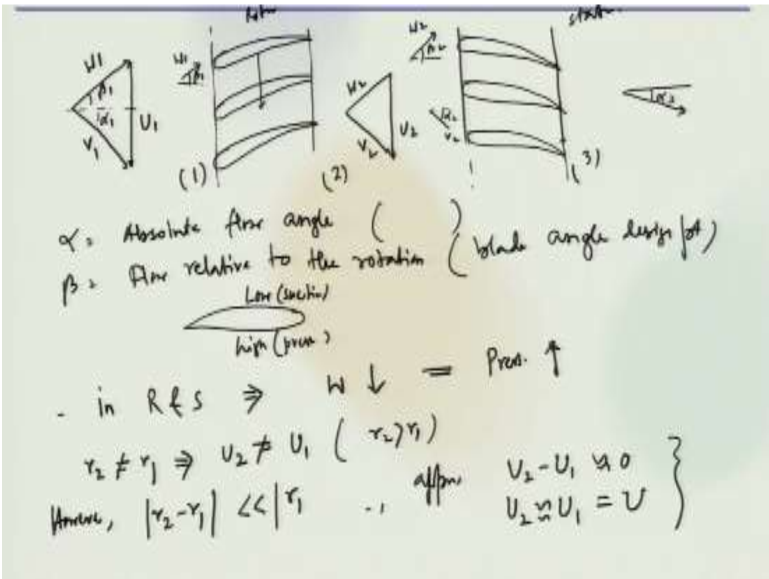

So, if that happens then what we can see that we have let us say here is the series of rotor blade which are sitting there. So this is the direction of the rotor then here would be the series of stator blade. So that is important so this is stator now this could be now the velocity triangle if I look at it so this goes this comes down so this would be U_1, V_1, W_1. So β_1, α_1 so this is what happens to β_1.

So this is at station 1 and then station 2 you have this triangle again so this is U_2, V_2, W_2 so this is what happens α_2, V_2 and this is W_2, β_2 and at 3 this is α_3. So alpha is the absolute flow angle so this is to the axial direction, β is the flow relative to the rotation so this is blade angle design point. Now angular momentum changes as the fluid travels through a blade rho because of pressure forces on the blade surface.

So pressure on the convex surface is relatively low, on the concave surface is relatively high and this pressure gradient give rise to the change in angular momentum. So if you look at the blade surface this is how it may look like, but this is the low side which is suction side this is the high pressure side, this is the pressure side. Now between 1 and 2 tangential component of absolute velocity increases rotor impacts the angular momentum to the air.

So in both rotor and stator so in rotor and stator W decreases so pressure increases. So typically in a radial displacement of fluid particle as it moves through a rotor blade rho strictly speaking r_2 should not be r_1 which means U_2 should not be U_1 and as shown $r_2 > r_1$. However, $r_2 - r_1$ smaller than r_1. For the simplicity of the discussion the approximation made here is that

$$U_2 - U_1 \approx 0$$

so

$$U_2 = U_1 = U$$

So this is the approximation which is met for the simplicity and to keep the discussion.

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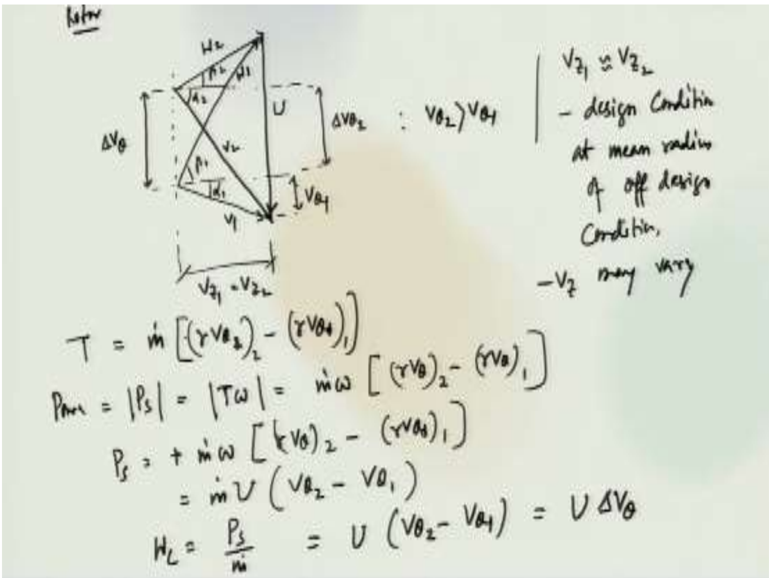

Now let us look at the velocity triangle at leading and trailing edge both of the rotor so this is at rotor. So we have this and so this means this will go like that and that will go like that. So this is there so this is W_2, this is U, this is V_2, this is W_1, this is V_1, this β_1, α_1, β_2, α_2 and this difference is ΔV_θ and this is $V_{\theta 1}$ so this is $V_{\theta 2}$ would be $V_{\theta 2} > V_{\theta 1}$ and this component is V_{z1} which is V_{z2}

Now what we say here V_{z1} would be V_{z2} so this is an design condition at mean radius of off design condition, but V_z may vary. Now if the velocity vectors of a particular particle crossing the rotor is given as we have shown here so we can calculate the torque. So now from angular momentum what we can write that

$$T = \dot{m}[(rV_\theta)_2 - (rV_\theta)_1]$$

so that is what you can write.

So the power would be

$$Power = T\omega = \dot{m}\omega[(rV_\theta)_2 - (rV_\theta)_1]$$

So the P_s would be so this is one can write this one as

$$P_s = \dot{m}\omega[(rV_\theta)_2 - (rV_\theta)_1]$$

$$P_s = \dot{m}U[V_{\theta 2} - V_{\theta 1}]$$

Now you can find out the work done per unit mass which is

$$W_c = \frac{P_s}{\dot{m}} = U[V_{\theta 2} - V_{\theta 1}] = U\Delta V_\theta$$

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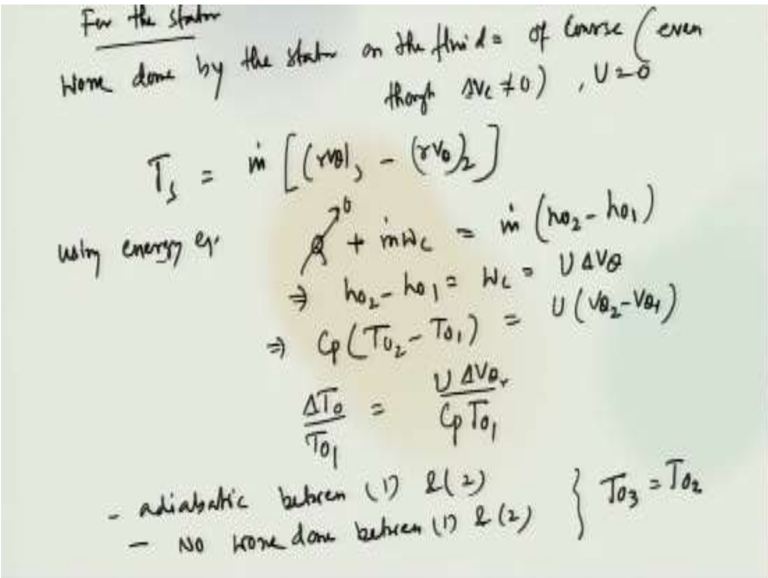

Now similarly so this is rotor for the stator we can so here the work done by the stator on the fluid equals to of course even though$\Delta V_e \neq 0$ so U=0. There is however torque on the stator opposite to that on the fluid so the

$$T_s = \dot{m}[(rV_\theta)_3 - (rV_\theta)_2]$$

Now flow between the station 1, 2, 3 is close to adiabatic because the heat transfer is almost negligible compared to the work done.

So now if we use the energy equation so this is adiabatic which will be

$$Q + \dot{m}W_c = \dot{m}(h_{02} - h_{01})$$

$$h_{02} - h_{01} = W_c = U\Delta V_\theta$$

So

$$C_p(T_{02} - T_{01}) = U[V_{\theta 2} - V_{\theta 1}]$$

So what we get here that

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

Now flow is since the flow is adiabatic between 1 and 2 so no work done. So flow is adiabatic between 1 and 2 no work done between 1 and 2. So what we will get T_{03} is T_{02} so which represents the entire stagnation temperature rise across the stage.

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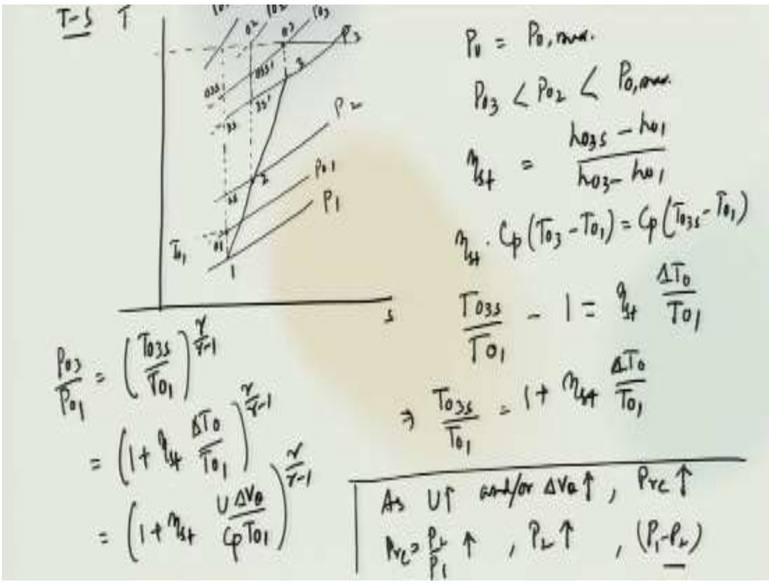

So if we draw the TS diagram. So this will look like so this is 0.1 which will go P_1 so 1 to 2 so this is P_2 2 to 3 so this is P_3. So this is P_{03} so this is 03 so this is 2 then P_{01} so this is 01 and this is 2s then this is 3s then this is 03s. Now from 2 if we go here so that would be 3s prime 03s prime so this is 02 so this P_{02} and this is P_{0max}. So these are all the points how it looks like and this is where you have T_{01} and this is 1.

So that is how and if the whole process is isentropic so

$$p_0 = p_{0,max}$$

So that the final stagnation pressure for the same work input would be $p_{0,max}$ but there are losses in rotor and stator so

$$p_{03} < p_{02} < p_{0,max}$$

Now if we look at the total stage efficiency which is this

$$\eta_{st} = \frac{h_{03s} - h_{01}}{h_{03} - h_{01}}$$

So this will determine the actual pressure rise by definition. So one can write

$$\eta_{st} C_p (T_{03} - T_{01}) = C_p (T_{03s} - T_{01})$$

So we get

$$\frac{T_{03s}}{T_{01}} - 1 = \eta_{st}\frac{\Delta T_0}{T_{01}}$$

So we get

$$\frac{T_{03s}}{T_{01}} = 1 + \eta_{st}\frac{\Delta T_0}{T_{01}}$$

Now we can write the

$$\frac{p_{03}}{p_{01}} = \left(\frac{T_{03s}}{T_{01}}\right)^{\frac{\gamma}{\gamma-1}}$$

and if we replace this then so this would be

$$\frac{p_{03}}{p_{01}} = \left(1 + \eta_{st}\frac{\Delta T_0}{T_{01}}\right)^{\frac{\gamma}{\gamma-1}}$$

so this would

$$\frac{p_{03}}{p_{01}} = \left(1 + \eta_{st}\frac{U\Delta V_\theta}{C_p T_{01}}\right)^{\frac{\gamma}{\gamma-1}}$$

So this is what you get. Now one can see as U increases so and or ΔV_θ increases P_{rc} also goes up. So P_{rc} means P_2/P_1 goes up which means P_2 goes up and obviously P_1–P_2 also to some extent goes up. Now this is true only up to a point.

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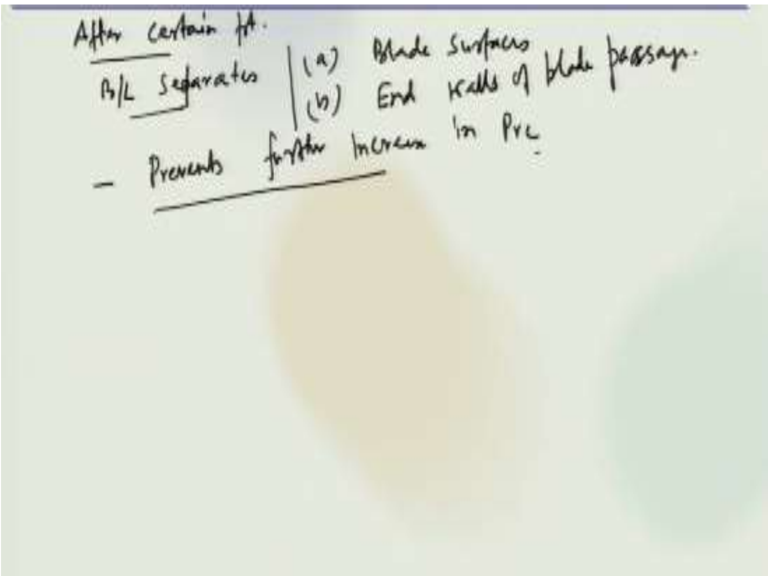

Because beyond certain limit there could be after certain point the boundary layer separation would occur so boundary layer separates a at blade surfaces b end walls of blade passage. So these are the two conditions which would be beyond certain point of this pressure rise this may possibly happen when the boundary layer separates and you have blade surfaces and end walls of blade passage where the boundary layer separation takes place.

So this actually prevents further increase in P_{rc}. So you can see that it is not an indefinite that you can keep on increasing P_{rc} up to any limit that you wish. So there are certain restrictions which may come like there could be flow separation and rather boundary layer separations in the blade surface and end wall effect would be there. So this will actually restrict the indefinite increment in the pressure rise. So we will stop here and we will continue the discussion in the next lecture.