Introduction to Airbreathing Propulsion
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Lecture – 55
Axial Turbine

So, let us continue the discussion on turbo machinery we have so far completed centrifugal compressor, then axial flow compressor and what we have looked at that what essentially turbo machinery is all about and what these compressors like centrifugal and axial compressors and their comparison not only from the operational point of view also, towards the end of the previous lecture.

We have discussed about the different material that is required for fabrication of different components of this compressor. It is not like that, then one individual material that can be used for designing those components and in top of that, what we have looked at the characteristics which are very important, then we have also looked at the different design procedure, some of them are important parameters that affect the design and how to mitigate those issues.

And in a nutshell, one can have an idea about those compressor performance and operation. I mean just to give you a quick refreshing of the memory, if you recall the compressor performance, they are limited by 2 different limits, one is the surge limit and another is the choking limit and within that band compressor has to operate. And what happens at the surge limit that when the compressor goes on stall and then it moves to rotational stall, and once the rotating stall can lead to surge.

So which will lead to a lot of unsteadiness, and then choking is that after a certain point of time the mass product cannot be enhanced anymore. So now why we are talking about all these details like compressor and compressor performance and their design, because this is one of the important component of the aircraft engine, because when the air comes in or rather suck into the system, compressor is the element or the component which actually compress the air.

So that you get proper pressure rise and then after compressor the component which comes into the system is the combustor. And then we already have discussed that what happens in the combustor that you need to have the slow airflow speed there. If you airspeed is too high then it would have a lot of difficulties in stabilizing the flame and other issues. And then just to extract the power output we have turbine.

Now since we have done discussion on compression. Now we are going to talk about turbine. At turbine actually operates in a completely opposite fashion. In a compressor, you actually get the proper pressure rise. But in the turbine actually, it is an expansion process where you extract the energy out but having said that, at the same time turbine is also a rotating machine or rather turbo machine. So, we will now continue our discussion on the turbine and we will look at performance and other stuff.

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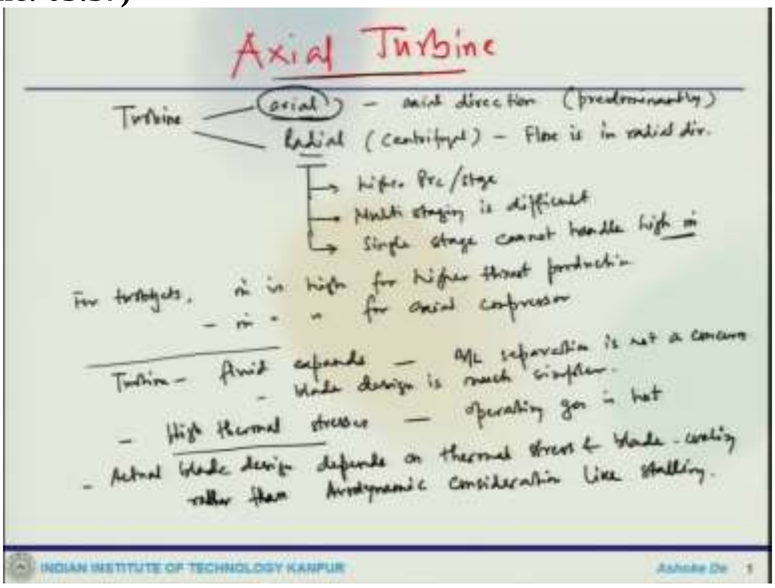

So what we will start doing that we will look at the axial flow turbine. So this is what we are going to talk about, but at the beginning, let me again reiterate that fact. That turbine also could be 2 types. That means it could be axial or it could be radial. So, which; is sort of what we talked about centrifugal compressor. So, this could be radial and this could be also axial. So we will start with the discussion on the axial turbine.

Then later on we will also touch upon some of the discussion on radial turbine too. So, here in the radial turbine the flow is in radial direction, so that is the important thing. And axial turbine obviously the flow predominantly in axial direction, so the predominantly this is in axial direction. Now, radial turbine can provide higher pressure ratios per stage. But this will have it can like your compressor; it can provide higher P_{rc} per stage.

But multi staging is difficult. So that is one of the biggest bottleneck. And the thing is that top of that the issue with the single stage is that that single stage cannot handle high m dot. So that is another bottleneck. Because once your mass flow rate is high, then the single stage would not be able to handle that. Now, obviously, one can note the total mass flow rate in engine is limited by the maximum permissible Mach number entering the engine.

Now, let us say for turbojet the mass flow rate is quite high to provide high thrust and m dot is also high for axial like compressor. So, for turbojet like $\dot{m}$ is high for higher thrust production secondly $\dot{m}$ is high for axial compressor too. So multi staging is also difficult for radial, but works for high P_{rc}. So, the reason here why we will talking about all these is that like compression, also the axial flow turbines are predominantly used in gas turbine industry.

So, here the thing is that sometimes it may be possible that even the combinations of radial compressor, axial turbines are used instead of radial turbine. Now, in turbine what happens the fluid undergoes pressure drop across the turbine. So, the turbine the fluid expands or rather the pressure drop takes place. So, here boundary layer separation is not a concern, since this is the fluid is expanding there and it undergoes the pressure drop.

So, the boundary layer separation is not a concern. And so, the blade design is much simpler. So, that is the advantage that you have with the turbine. So, here you do not have the possibility of sort of having stall or such kind of problem that you see in the compressor. So, this is sort of not existence, issue in turbine. But obviously, that does not mean the turbines are free of any problems.

The issue, which turbine actually face that high thermal stresses. So, the blades actually are exposed to high thermal loading or higher thermal stresses because the operating gas is hot. Now, if you recall turbine is a component which is connected downstream of the combustor. So, whatever the combustion product and the hot exhaust gas that comes out of the combustor and comes out of combustor to enter in the turbine, they are extremely hot.

So, the thermal loading or the thermal stresses are quite high for turbine instead of the other issues like boundary layer separation or such things like that. Now, so, one can immediately think about the actual blade design. So, that depends on thermal stress and blade cooling other than aerodynamic consideration like stalling. So, you can see there is an immediately difference in the approach.

When you go to compressor to turbine because the turbine blades are exposed to higher thermal load or thermal stresses and also the cooling of the blades how efficiently or effectively the cooling is done. So, obviously they are not considering the effect of stalling is that important in this case and also the other issues? So, the other thing is that the velocity triangle requirements also have to be satisfied.

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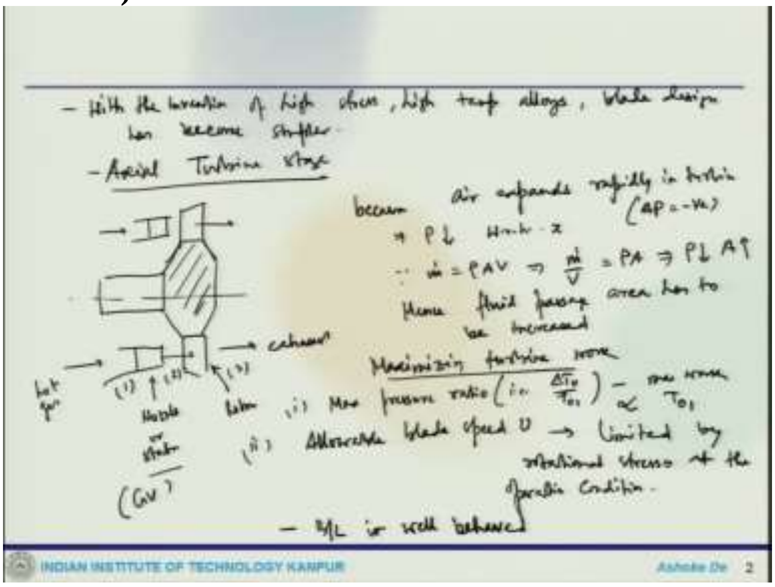

Now the invention of high stress, high temperature alloys, blade design has become simpler. So they can now operate at the high temperature and that provide the proper engine thrust with to that specific fuel consumption all this. Now, we will look at axial turbine stage. So let us say we just draw a schematic here. So this is the entering of the hot gas. Let us say 1 this is sort of nozzle or stator. Then it goes here, this is station 2 and this is the rotor.

So, this is exhaust. So, this is the station 3. So, that is the schematic. Now as in axial compressor also axial turbine has the stator and rotor. Here the stator is essentially the guide vanes, also called nozzles, but in axial compressor the blade height decreases with axial distance in turbine the blade height actually increases with distance. So, there is a completely reverse thing that takes place with both the situation.

So, that happens because air expands rapidly in turbine. So, Δp is favorable or favorable pressure gradient. So, which means density actually goes down. So, with respect to; let us say x or the distance. Now to; maintain the constant axial velocity. Now, it has to be increased since mass flow rate is

$$\dot{m} = \rho AV$$

So,

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

Now as ρ goes down, A has to go up. Hence one can see the fluid passage area has to be increased.

Now how do we maximize the turbine work? So, it can be now maximizing turbine work. So, this can be limited by 2 cases. Number 1 maximum pressure ratio. So that means $\frac{\Delta T_0}{T_{01}}$. So, maximum work is directly proportional to T_{01} at 2 allowable blade speed U which is limited by rotational stresses at the operating conditions. So, here the one can think about the boundary layer is well behaved. So, there is no issue such like boundary layer separation.

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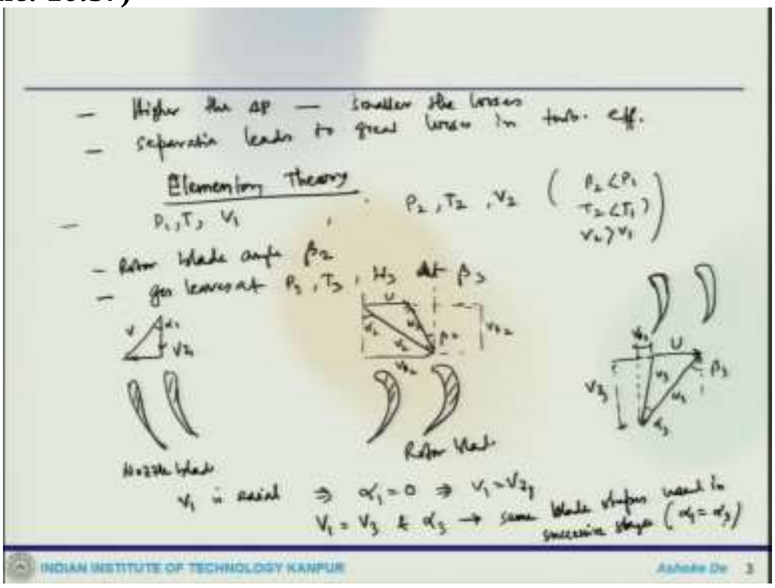

So, what happens at higher the pressure drop or other higher the Δp pressure drop. So the smaller the losses that is number 1. Second separation leads to great losses in turbine efficiency. Now, high turning of the flow in the passage in highly twisted blade may cause some 0 or adverse pressure gradient in some passage. So, therefore, boundary layer may separating those passage at high rotational speed. But separation leads to greater loss in thermal efficiency, but that is very rare. But still, these are some of the things.

So now, with that, we will look at the elementary theory. So let us consider a gas entering a row of nozzle, a blade with P_1, T_1 and V_1. And it leaves at station 2 P_2 T_2 and V_2. Where, P_2 would be less than P_1. T_2 would be less than T_1 and V_2 would be greater than V_1. Now the rotor blade angle that is β_2 it shows that gas enters the passage smoothly. Now after being deflected and for an after further expansion in rotor blade passages, gas leaves at P_3 T_3 and relative velocity W_3 at angle β_3.

So, gas leaves at P_3 T_3 W_3 and at β_3. So, let us see how that looks like. So, we have these nozzle blades. So the velocity triangle would we like this. So this is V, this is α_1, this is the V_{z1}. Now, we have these rotor blades. So here the velocity triangle has this this. So, this, this so, this is U this is α_2, so this is V_2, this is β_2, W_2, V_{z2} this component is $V_{\theta 2}$ and then finally it goes like this.

So U, W_3, this is β_3, V_3. So this one is α_3, this is $V_{\theta 3}$ and this component is the V_{z3}. So, that is now in a single stage turbine, V_1 is axial, which means α_2, =0, V_1=V_{z1}. So, now if the stage is part of multistage then V_1 = V_3 and α_3 which is means the same blade shape used in successive stages. So, same blade shapes used in successive stages which means, $\alpha_1 = \alpha_3$.

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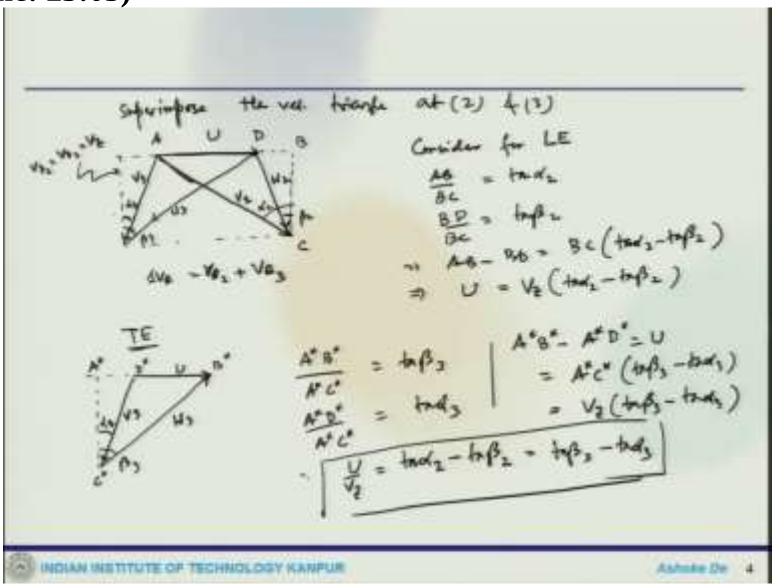

Now consider the flow at mean radius. Now, if we suppose superimpose the velocity triangle, let us say superimpose the velocity triangle at 2 and 3. So, which will look like we have this component now like this that goes here. So this is U. So, this is U this is W_2, this is V_2. Now, this is point A, this is let us say point B, this is point B this is C and this is α_2 and this is W_3 and this is V_3.

So, this component is essentially V_{z2}, which is V_{z3} is V_z. So, this component is like that and this is α_3 and this guy is the β_3 that is β_3. So, and this is α. So, there is β_2 so you can see that V_{z1} that α_1. So, V_2 will have that α_2 and W_2 we will have the β_2. So, this is β_2 and this is W_2. So this is β_3, this is W_3. So here are what we can say that

$$\Delta V_\theta = V_{\theta 2} + V_{\theta 3}$$

Now, let us say consider for leading edge. So,

$$\frac{AB}{BC} = \tan \alpha_2$$

And

$$\frac{BD}{BC} = \tan \beta_2$$

So, what do we get

$$AB - BD = BC(\tan \alpha_2 - \tan \beta_2)$$

$$U = V_z(\tan \alpha_2 - \tan \beta_2)$$

Now, similarly trailing edge the triangle would be slightly different. So, this is W_3. So, this is V_3. So, this one is β_3, this one is α_3 this is $A^*, D^*, U,\ B^*, C^*$

Now, a trailing edge

$$\frac{A^*B^*}{A^*C^*} = \tan \beta_3$$

and

$$\frac{A^*D^*}{A^*C^*} = \tan \alpha_3$$

So,

$$A^*B^* - A^*D^* = U = A^*C^*(\tan \beta_3 - \tan \alpha_3) = V_z(\tan \beta_3 - \tan \alpha_3)$$

So, since

$$\frac{U}{V_z} = \tan \alpha_2 - \tan \beta_2 = \tan \beta_3 - \tan \alpha_3$$

So, this is what we get when we combine this triangle. Now, we will continue this some discussion in the next lecture.