Introduction to Airbreathing Propulsion

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Lecture - 35
Performance/Cycle Analysis: Turboshaft and Propfan

So we have started discussing about the turboprop engine, then now we are going to move to the turboshaft engine and then we will continue with some of the other parts, but let us look at the turboshaft.

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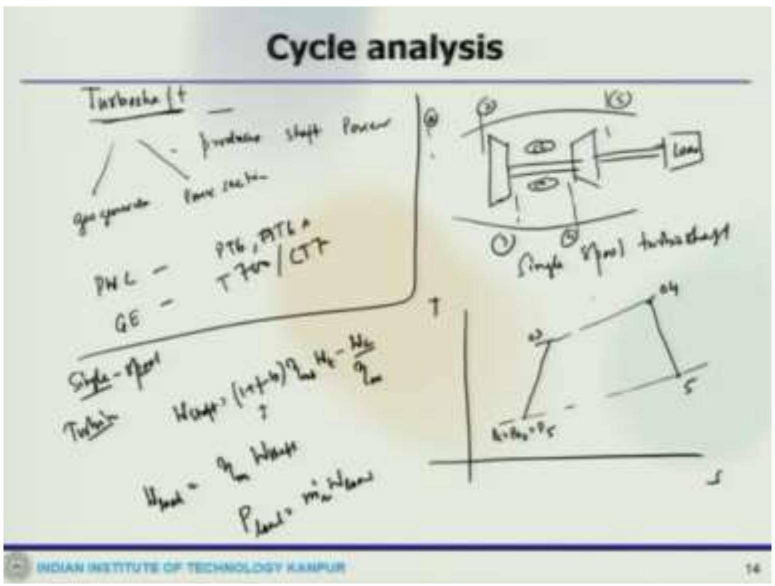

Because what we have finished like the comparison with the turboprop with the turbofan and now we are going to look at the turboshaft. So this is also going to be a small section. This also kind of engine is a form of gas turbine, which is optimized to produce shaft power other than jet thrust. So this produces shaft power not the jet thrust. Generally, a turboshaft engine is made up of two major components; one is the gas generator, another component is the power section.

So the gas generator consists of one or more compressor, combustor chamber or turbine and the power section actually consists of an additional turbine or a gear reduction system and the shaft output. So there are different example of turboshaft manufacturer like one is the biggest is Pratt & Whitney, they have PT6 and PT6A; these are the engines. Then GE also manufacture some of this like it has A61, A62, so that power this aircraft. So the engine is T700 or CT7.

These are the engine. Then also Allison Engine company, Lycoming, Rolls Royce all these and also the Soviet also they also manufacture this kind of turboshaft engine. Just to look at the analysis of a turboshaft engine, let us see if we look at a single spool engine, then the engine schematic will look like this. We have like then there is a turbine sitting there, then you have the load. So this is a single spool turboshaft schematic. So one can think a, 2.

There is the combustion chamber and then 3 this is 4, 5. So you can see this the load is driven by the same gas generator shaft or given by the free turbine. So this is a single spool configuration and the similar one we can. So the TS diagram if we plot of the same engine, it will look like starting from here it will go there and then from there it will come here. So this is 3, here the Pa is $P_{02} = P_5$; this is 5, this is 4. So if we look at, so it has we can single spool engine.

So this is some analysis would be quite similar to turboprop. Now what we can do the single spool engine, we can look at the turbine. The turbine drives both the compressor and the load. So assuming full expansion in the turbine. So the shaft power would be

$$W_{shaft} = (1 + f - b)\eta_{mt}W_t - \frac{W_c}{\eta_{mc}}$$

where f is the fuel air ratio, b is the bleed ratio and the mechanical efficiency is η_{mt}, compressor efficiency is η_{mc}.

Now the shaft which drives the load, it could be the load which means let us say for example the rotor of the helicopter experiences some of the mechanical losses due to friction. So the

$$W_{load} = \eta_m W_{shaft}$$

So then we can find out the

$$P_{load} = \dot{m}_a W_{load}$$

So that is how we can get it.

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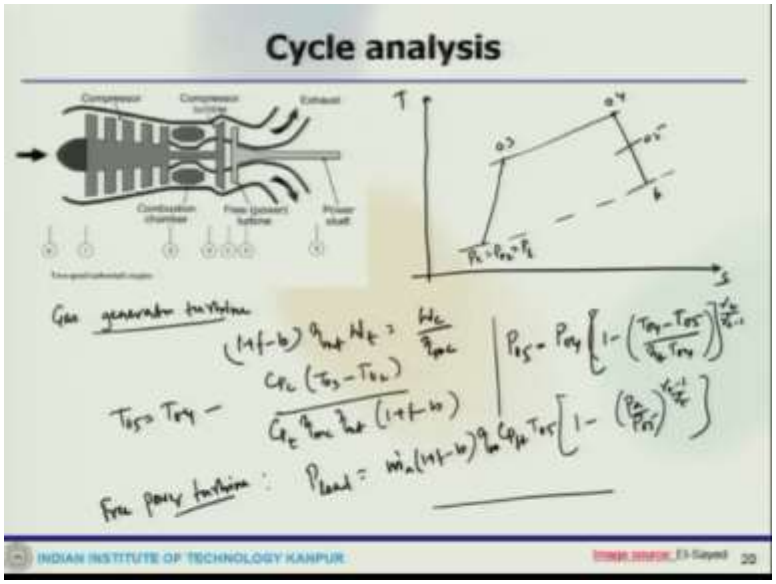

Now similarly like a single spool, we can have a two spool turboshaft also and there is a different station number and if you draw the TS diagram similarly here, this is where from where it goes like that so this is 3, this is 4 and this is 5, this is 6, P_a, P_{02}, P_6. So now the twin spool also, now if you look at the gas generator turbine. So if you have the gas generator turbine, so that point provides sufficient energy to drive the compressor.

Thus the outlet temperature is obtained from the energy balance and how do we get it is a simple similar analysis that we have done.

$$(1+f-b)\eta_{mt}W_t = \frac{W_c}{\eta_{mc}}$$

so that gives that

$$T_{05} = T_{04} - \frac{C_{Pc}(T_{03} - T_{02})}{C_{Pt}\eta_{mt}\eta_{mc}(1+f-b)}$$

and similarly we get

$$p_{05} = p_{04}\left[1 - \frac{(T_{04} - T_{05})}{\eta_t T_{04}}\right]^{\frac{\gamma_t}{\gamma_t - 1}}$$

So now the free power turbine if we look at, the gases are basically have a complete expansion to the ambient pressure.

So the power delivered to the load would be

$$P_{load} = \dot{m}_a(1 + f - b)\eta_{mc}C_{Pt}T_{05}\left[1 - \left(\frac{p_a}{p_{05}}\right)^{\frac{\gamma_t - 1}{\gamma_t}}\right]$$

So that is how the analysis actually holds for turboshaft engine. Now so that is how you can have single pool or double spool turboshaft; the other component detail analysis we can carry out in the similar fashion that we have done for turboprop or any other turbine engines.

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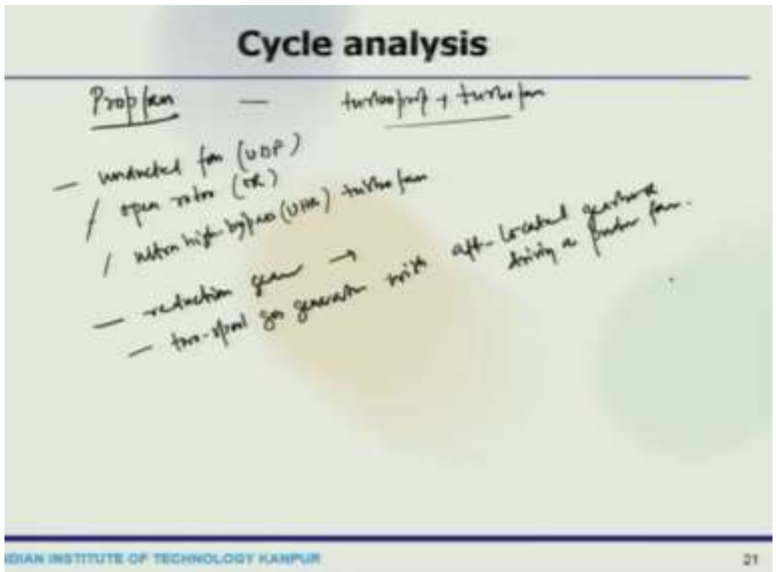

Now that will move to the one which is propeller fan. So this is a modern type of aircraft engine related to concept of both the turboprop and turbofan. So that somehow uses both the concept of turboprop plus turbofan. So that is sort of a combination, but distinct from both. The engine uses a gas turbine to drive a unshielded propellant like a turboprop, but the propeller itself is designed with a large number of short highly twisted blades similar to the turbofan engine.

For this reason, the propeller fan has been variously described as this could be called as unducted fan UDF or called open rotors which is OR or it could be called ultra high bypass that is UHB turbofan. So this could be also said like that. Now it has a small diameter highly loaded multiple bladed variable pitch popular propulsor having swept wide quad blades. So propeller fan is designed to operate with a turbine engine and using a single stage reduction gear.

So it has a reduction gear that results in high performance. So the performance is high. So the design is sort of intended to offer the performance of a turbofan with the fuel economy of turboprop. So most common arrangement of propeller fan is a two spool gas generator and after located gearbox driving pusher fan. So with aft located gearbox driving a pusher fan. So this fan produces the majority of the thrust.

It has number of blade which is greater than the propeller of turboprops, but less than those of fan in the turbofan. Similarly, one can see like there are also some historical things. There is a history behind this kind of thing, so like some old.

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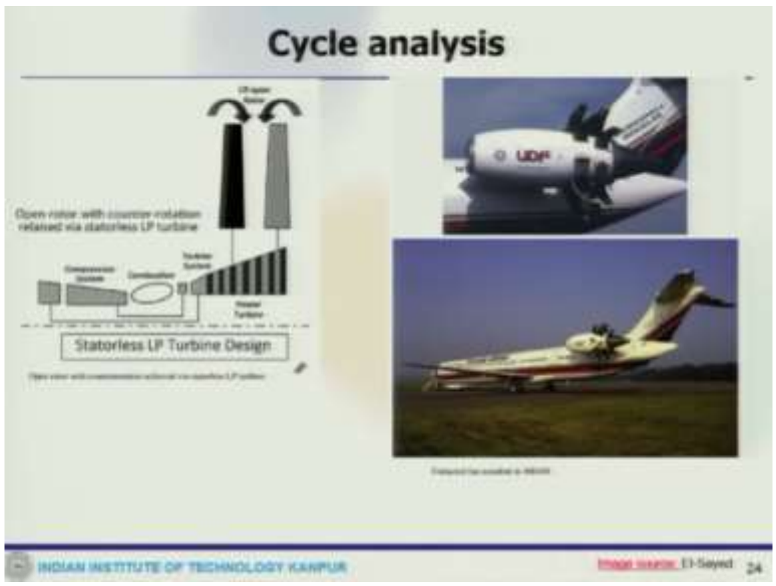

Like here is an example of open rotor, so this is like this is a GE introduced this unducted G36. This is an aft mounted open rotor fan system with two rows of counter-rotating composite fan blades. So this was in 1980s. It is of the pusher configuration. The core was based on GF04 military turbofan and so exhaust gases were discharged through a seven stage LP turbine. Each stage ring was designed to move freely.

So the turbine rotor driven on propeller while the other propeller is connected to the turbine stator and all this. So the total in effect that power turbine has 14 stages, which you can see here. Now the other one, which one can see is also the one which is shown here, which is unducted fan in MD80. So this is another one which is example of that nature. So Pratt and Whitney engine one can see. Also there are I mean other engine manufacturer, which also they produce some engines of this kind of propeller fan and they are in to some extent.

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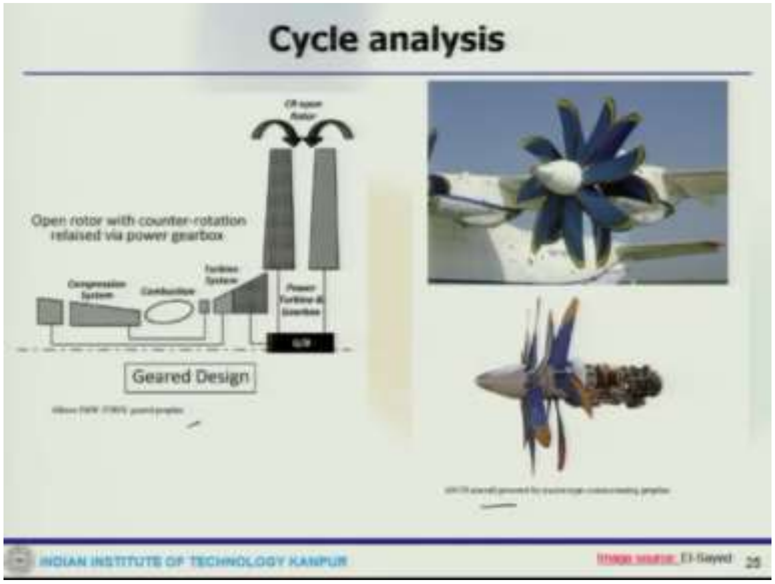

Like this is another one which is Pratt and Whitney 578DX which is 1980. This is also having a reduction gearbox between LP turbine and the propeller blades. So some progress been made. So this is our D27 propeller fan. So this was developed by USSR. So this is even conventional in layout with propeller fan blades in front. So it is used for propelling AN70 aircraft. so this was used for AN70 aircraft.

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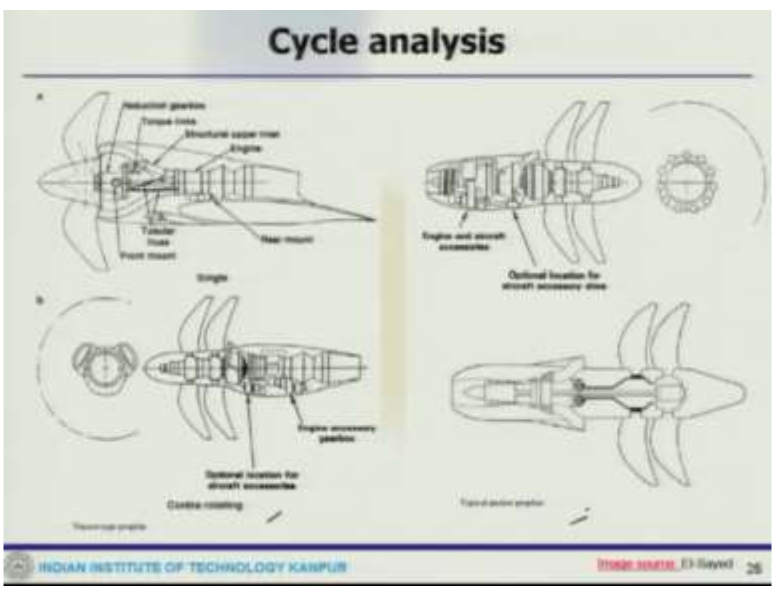

So typically if you look at the classification of the propeller fan, there are two different types one is the tractor type. So if I look the prop fan, then there could be tractor type or it could be pusher type. So these are the two different category which can be possible and the tractor type propeller fan is similar to; so this is one of the kind like it could be saying the tractor type or you can say puller type. So this is a similar to forward fan with the fan placed.

So this is again the tractor fan can have two different kind; one is the single and another is the contra-rotating or counter-rotating whatever it is. So the example of contra-rotating is this one. You can see this is the contra-rotating, so that is what is shown there. This forward rotor has eight bladed, while the rear is six bladed and the pusher type if one has to see this is a pusher type typical arrangement of the turbofan where it is similar to the aft fan where the fan is coupled to the turbine.

It is always of the contra-rotating type. So the two fan rows are driven by free turbine. This type would be more elegant as the engine would be placed behind the rear pressure bulkhead in the fuselage minimizing the noise. It also allows an aerodynamically clean wing.

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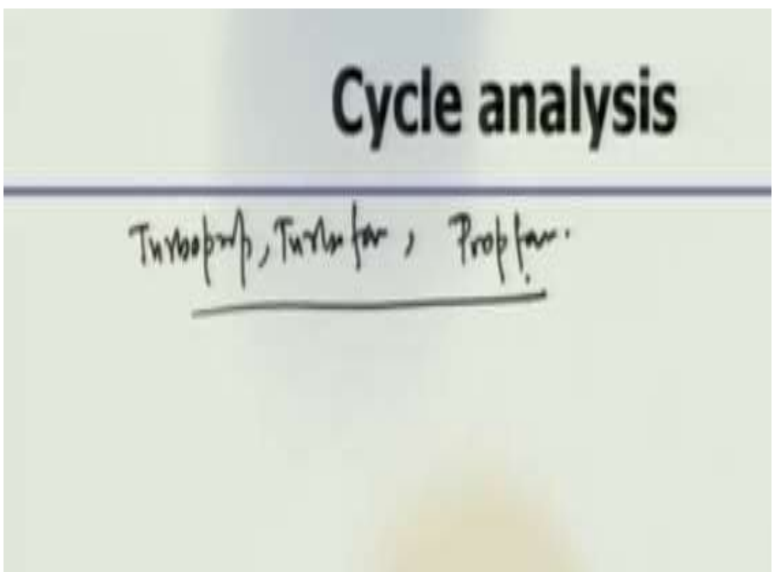

Now, one can compare this like between turboprop, turbofan and propeller fan. So if you compare that propeller fan engines have the best known propulsion efficiency. Single rotation propeller engines have propulsion efficiency around 80%, while contra-rotating can go up to 90%. So main feature of propeller fan engine versus both turboprop and turbofan engines are quite significant.

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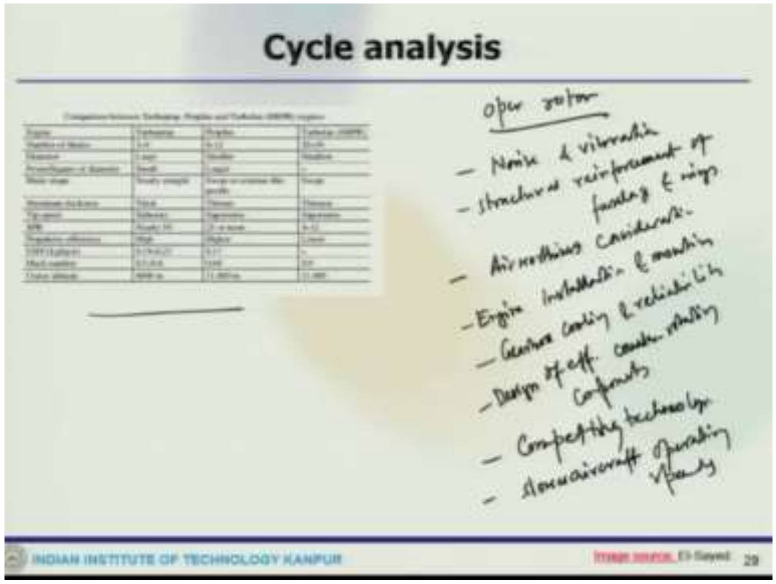

Also we can see that like for example we can go here and see this comparison between all these turboprop, turbofan and you have this, but you can see the propeller fan, number of blades compared to turbofan less, but more than these, diameter is smaller, power is larger, blade type swept, maximum thickness thinner, tip speed supersonic, bypass ratio is 25, propulsion efficiency higher, ESFC is their Mach number is around 0.7687, cruising altitude is 11,000.

But open rotor play some pose some technological challenges which like the open rotor kind of configuration like noise and vibration like then structural reinforcement of fuselage and wings. So air worthiness consideration, engine installation and mounting gearbox cooling and reliability, then design of efficient counter rotating components. So these are some of the challenges with then competing technologies, because obviously that is another competing technologies.

So the current technology engine is improving on an average 1% per year, which means that traditional turbofan engine available in 2020 are likely to be at least 11 percent more efficient than 2010 production. So that is a major technological breakthrough, then another is the slower aircraft operating speed. So these are some of these challenges which are there and you can see these.

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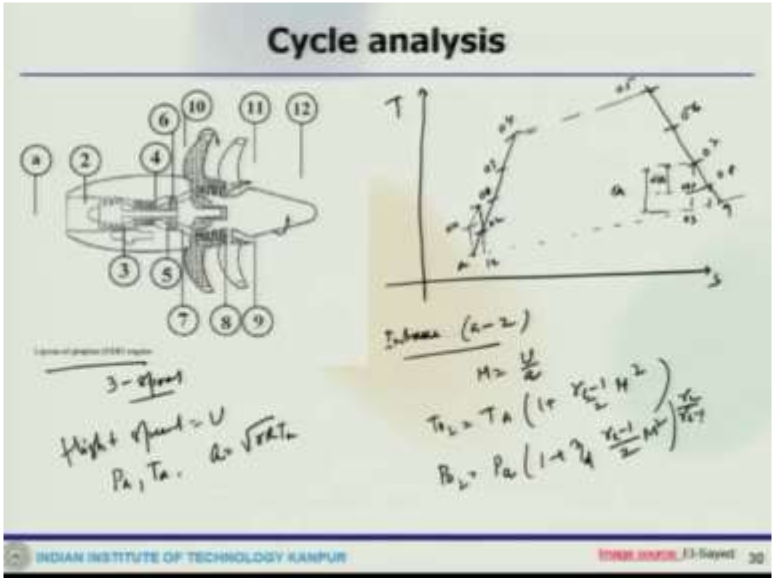

So the other thing what is also possible that there is a possibility of this is a three spool configuration. So that is also possible. This is the unducted 3 spool configuration and you have all these kind of, I mean, this is just an example that this is also possible and you can have a TS diagram for these and you can similarly look at the analysis. So for example a to 2, 2 to 11 goes 3, this is 11, this is a, 02, 04, so this is 05, 06, 7, 8, 9, this one is 08s.

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This is Δh and this is $\alpha\Delta h$. Now this one would be 9s and here one can have, this goes right there, so this is 010 and that also connect to Ta, and this is 12. So these are the different portion. Now, one can do this analysis which could be quite sort of straightforward. So one has to look at first the intake, this is probably the last one that we would like to discuss on turbofan and that would pretty much finishes this.

So if you have, let us say the flight speed, which is given u and then ambient condition P_a T_a, then you can find out

$$a = \sqrt{\gamma R T_a}$$

then at the intake you can find out the Mach number

$$M = \frac{U}{a}$$

so you get the T_{02}, which is the relationship using that M square and P_{02}. So we have done this so many time.

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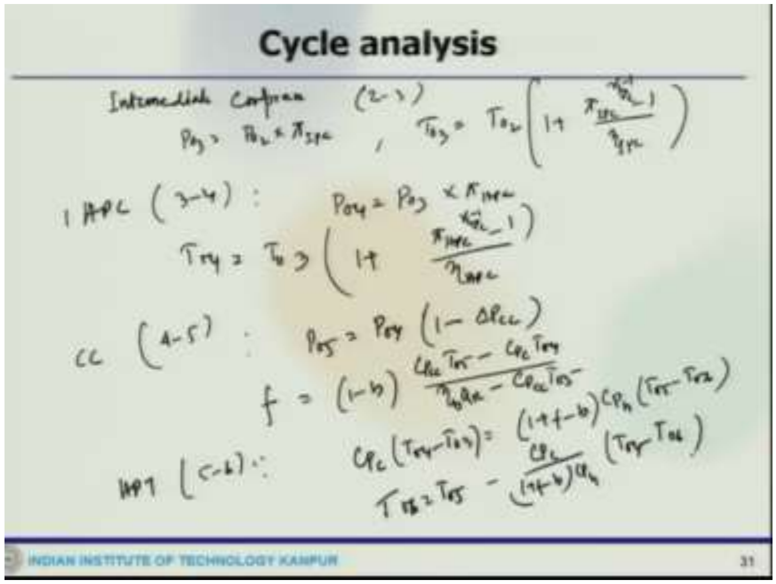

Now intermediate compressor, which is 2 to 3, so here

$$p_{03} = p_{02} * \pi_{IPC}$$

So

$$T_{03} = T_{02}\left[1 + \frac{\pi_{IPC}^{\frac{\gamma_c - 1}{\gamma_c}} - 1}{\eta_{IPC}}\right]$$

Now IHPC or high pressure compressor which is 3 to 4 so

$$p_{04} = p_{03} * \pi_{HPC}$$

So

$$T_{04} = T_{03}\left[1 + \frac{\pi_{HPC}^{\frac{\gamma_c - 1}{\gamma_c}} - 1}{\eta_{HPC}}\right]$$

combustion chamber which is 4 to 5 where

$$p_{05} = p_{04}(1 - \Delta p_{cc})$$

and

$$f = (1-b)\frac{C_{Pcc}T_{05} - C_{Pc}T_{04}}{\eta_b Q_R - C_{Pcc}T_{05}}$$

Then, HPT that is 5 to 6, so energy balance for high pressure pull from where we get

$$C_{Pc}(T_{04} - T_{03}) = (1 + f - b)C_{Ph}(T_{05} - T_{06})$$

So here we are assuming the transmission efficiency or the mechanical efficiency of the shaft and all these to be 100%. So from here, we get

$$T_{06} = T_{05} - \frac{C_{Pc}}{(1 + f - b)C_{Ph}}(T_{04} - T_{06})$$

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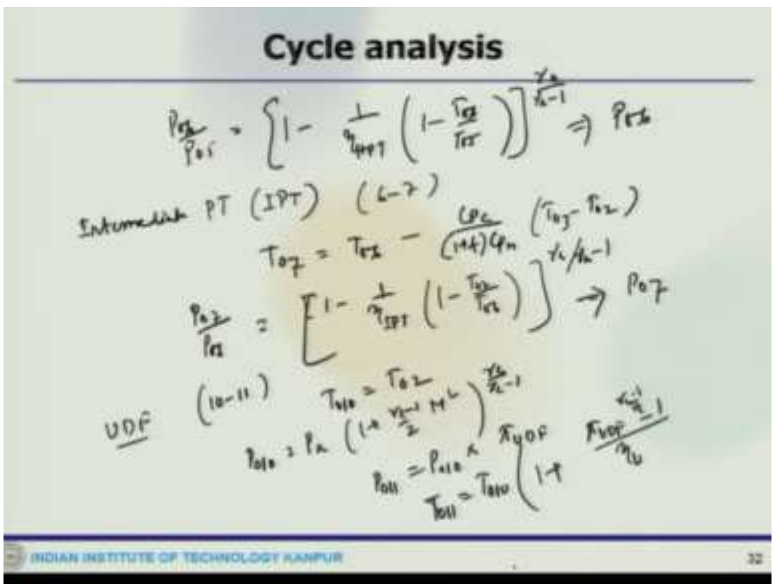

And

$$\frac{p_{06}}{p_{05}} = \left[1 - \frac{1}{\eta_{HPT}}\left(1 - \frac{T_{06}}{T_{05}}\right)\right]^{\frac{\gamma_h}{\gamma_h - 1}}$$

Then intermediate pressure turbine or IPT which is 6 to 7 again energy balance would give us

$$T_{07} = T_{06} - \frac{C_{Pc}}{(1 + f)C_{Ph}}(T_{03} - T_{02})$$

So we get the pressure

$$\frac{p_{07}}{p_{06}} = \left[1 - \frac{1}{\eta_{IPT}}\left(1 - \frac{T_{07}}{T_{06}}\right)\right]^{\frac{\gamma_h}{\gamma_h - 1}}$$

Then UDF or unducted fan, so here T_{010} is T_{02}, so

$$p_{010} = p_a\left(1 + \frac{\gamma_c - 1}{2}M^2\right)^{\frac{\gamma_c}{\gamma_c - 1}}$$

So

$$p_{011} = p_{010} * \pi_{UDF}$$

so

$$T_{011} = T_{010}\left[1 + \frac{\pi_{UDF}^{\frac{\gamma_c - 1}{\gamma_c}} - 1}{\eta_{UDF}}\right]$$

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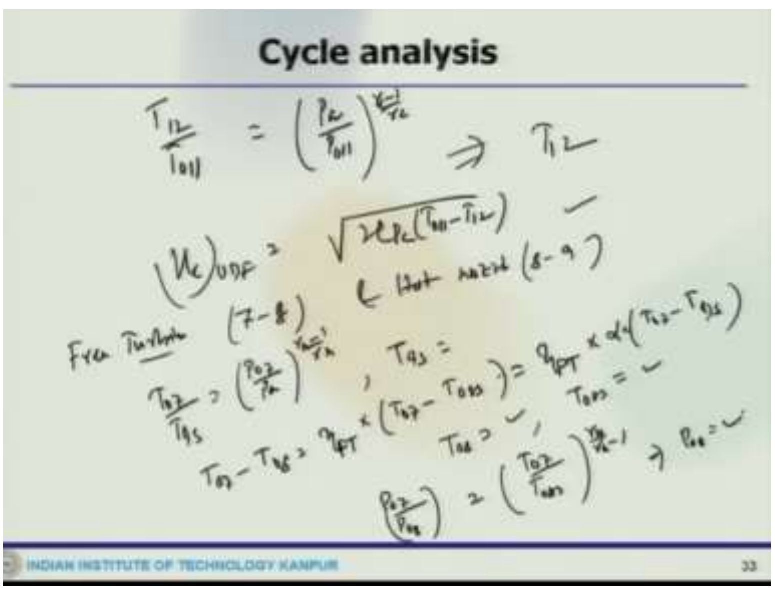

So what we get

$$\frac{T_{12}}{T_{011}} = \left(\frac{p_a}{p_{011}}\right)^{\frac{\gamma_c - 1}{\gamma_c}}$$

So from here, we get T_{12} so unducted fan, it would be

$$(u_e)_{UDF} = \sqrt{2C_{Pc}(T_{011} - T_{12})}$$

So that is what we get and once you get that, then we have free turbine which is 7 to 8 and hot nozzle, which is 8 to 9. So from here, we will write

$$\frac{T_{07}}{T_{9s}} = \left(\frac{p_{07}}{p_a}\right)^{\frac{\gamma_h - 1}{\gamma_h}}$$

which gets at 9s and then temperature drop in free turbine would be

$$T_{07} - T_{08} = \eta_{ft}(T_{07} - T_{08s}) = \eta_{ft}\alpha(T_{07} - T_{9s})$$

So we get T_{08}, we get T_{08s}, so from here we get the pressure ratio which is

$$\frac{p_{07}}{p_{08}} = \left(\frac{T_{07}}{T_{08s}}\right)^{\frac{\gamma_h}{\gamma_h - 1}}$$

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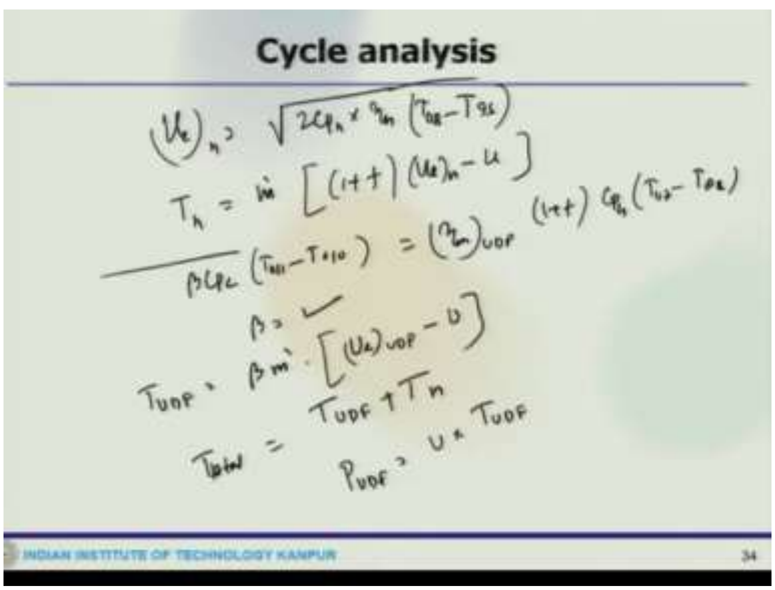

And then the nozzle exit velocity would be

$$(u_e)_n = \sqrt{2C_{Ph}\eta_n(T_{08} - T_{9s})}$$

Now so the thrust would give us

$$T_n = \dot{m}[(1 + f)(u_e)_n - u]$$

so that you get. Then finally energy balance would give us

$$\beta C_{Pc}(T_{011} - T_{010}) = (\eta_m)_{UDF}(1+f)C_{Ph}(T_{07} - T_{08})$$

So from here, we will get beta and then the thrust for which is obtained for

$$T_{UDF} = \beta\dot{m}[(u_e)_{UDF} - u]$$

So the total thrust would be

$$T_{total} = T_{UDF} + T_n$$

and the unducted power would be

$$p_{UDF} = U * T_{UDF}$$

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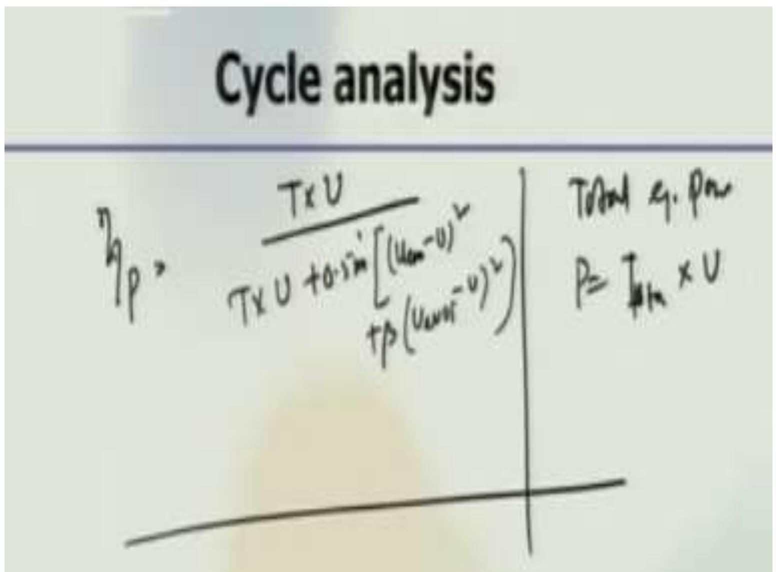

So that is how you can get and then finally you can find out the propulsive efficiency which is

$$\eta_P = \frac{T * U}{T * U + 0.5\dot{m}[(u_\infty - u)^2 + \beta(u_{UDF} - u)^2]}$$

So then you can get the propulsive efficiency, so that is how you also can analyze the three spool engine and that is pretty much kind of talks about this turboprop, turboshaft and turbofan engines.

And the analysis you have seen already this turbine-based cycles, how the analysis is carried out, so now you would be able to carry out the similar kind of analysis. So we will stop the discussion here and continue in the next session in the other topics.