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

Lecture – 31
Performance / Cycle Analysis: Turbofan (Contd.,)

Okay, so let us continue the discussion on turbofan engine. So we have looked at the performance analysis or the thermo dynamical analysis of turbofan engine. So, now there are different variant of turbofan engine which are possible so the one which now we are going to discuss now is the mixed flow engine.

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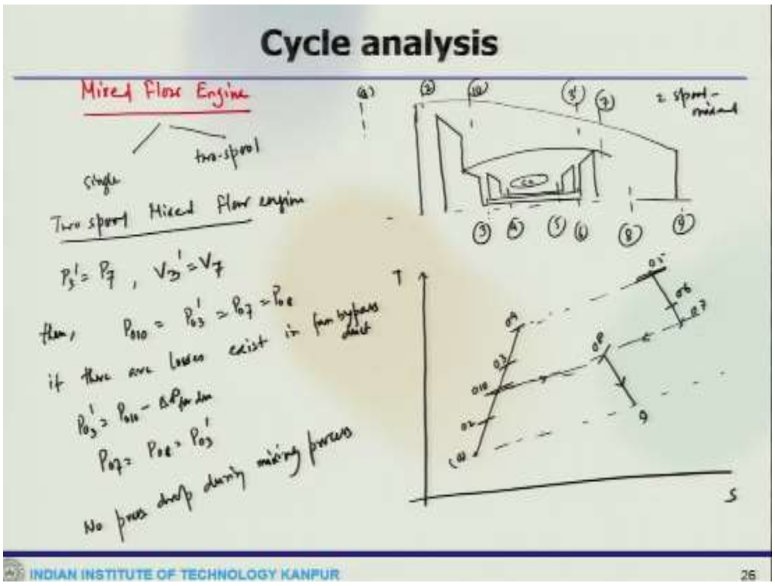

So then from mixed flow so this means that the mixed flow engines were which suggest as the name suggest that the hot and cold mixed gases they are mixed. So there could be of two types of that kind of engine either it could be single spool or it could be two spool. So, previously it was used in military application, but these days it is used in also civilian aircraft and pretty much in all military aircraft.

Typically, one of the example is CFM56 series which is a two spool engine of a civilian aircraft. So it is just like the cold air which is coming out of the fan for the cold part which is not going to be exiting out that will be mixed somewhere. So, let us look at that we start with the two spool mixed flow engine. So that we will just look at that then the single spool would be much more easier and if you look at the schematic so this would be the schematic of that.

Let us say we have this and then that goes out comes here and then we have this one comes here goes like that and then the second set which will be there this will go like this so here is the combustion chamber and then this is there. So now we can mark the station this is a typical layout of push pull mixed turbofan. So let us say this is station a this would be 2 then we come here that is 3 comes here 4, 5, 6.

Then 7 we have 8 and 9 we get 10 and somewhere 3 prime and the TS diagram for the same. If you look at that so we are starting here a goes to 02, goes to 10 then in between 03 goes 4, 5, 6, 7 so let us do it properly. So 7 somewhere 8 and then we get 9 so that is how the TS diagram would look like. So one requirement is that for the analysis mixing process or equal static pressures and also equal velocity.

Thus, from the layout what we can say two conditions are specified. One is

$$p_3' = p_7$$

and then what we do like another one is in the velocity is

$$V_3' = V_7$$

So which means there is no pressure loss in the bypass duct connecting the cold and hold stream and no pressure loss in the mixing process then what we can write is that

$$p_{03}' = p_{07} = p_{08}$$

Now if losses exist in the fan bypass duct if there are losses exist in fan bypass duct then what we can do

$$p_{03}' = p_{010} - \Delta p_{fan\ duct}$$

So one more thing so no pressure drop which is considered no pressure drop during mixing process. So that is another important factor that there is no pressure drop which are considered during mixing process.

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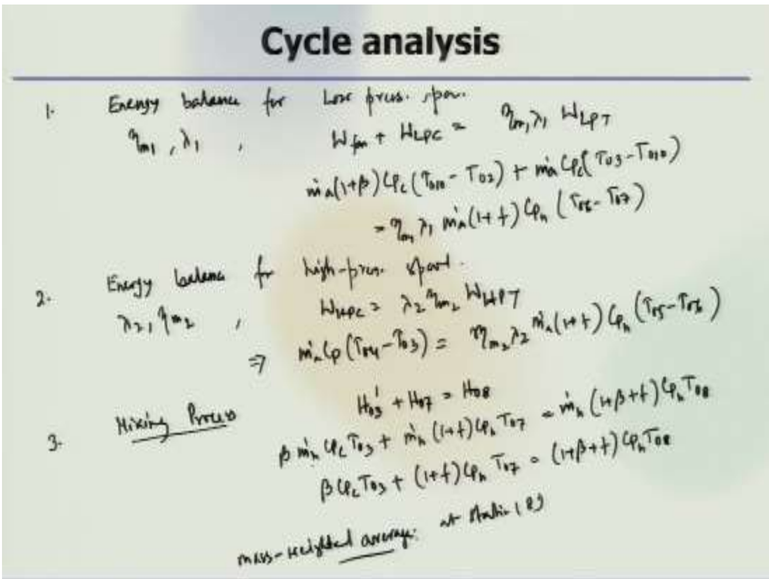

So what we can write now energy balance for low pressure spool. So, again we are considering the mechanical efficiency of η_{m1} and λ_1 would be the conversion factor then

$$W_{fan} + W_{LPC} = \lambda_1 \eta_{m1} W_{LPT}$$

So which straightway now we have enough expression or so far we have looked at in detail. So we will typically put it straight

$$(1+\beta)\dot{m}_a C_{Pc}(T_{010} - T_{02}) + \dot{m}_a C_{Pc}(T_{03} - T_{010}) = \lambda_1 \eta_{m1}[\dot{m}_a(1+f)C_{Ph}(T_{06} - T_{07})]$$

Similarly, if we do the energy balance for high pressure spool which is again we consider η_{m2} and λ_2 then what we write

$$W_{HPC} = \lambda_2 \eta_{m2} W_{HPT}$$

which straight away one can write

$$\dot{m}_a C_{Pc}(T_{04} - T_{03}) = \lambda_2 \eta_{m2}[\dot{m}_a(1+f)C_{Ph}(T_{05} - T_{06})]$$

So the third it is mixing process which one has to consider now in the mixing process what happens the hot gases leaving the low pressure turbine and the cold gases leaving the bypass duct are mixed.

So if you look at this, this is where this is the hot gases coming this is where the cold gases coming and then mixed at station 8. So both the core of the engine now from the first law of thermodynamic what we can write enthalpy at here plus 7 would be enthalpy at 8. So 7 is in the core and this is in here so what we write like

$$\beta \dot{m}_h C_{Pc} T_{03} + \dot{m}_h(1+f)C_{Ph}T_{07} = [\dot{m}_h(1+f+\beta)C_{Ph}T_{08}]$$

So this should be this is β is so $\dot{m}_h$ means whatever going through the hot portion of the engine so that gives us back

$$\beta C_{Pc} T_{03} + (1+f)C_{Ph}T_{07} = [(1+f+\beta)C_{Ph}T_{08}]$$

Now one can do that or basically like better evaluation of the gas properties after mixing. So we can do the mass weighted average. So mass weighted average so if you take at station 8 the mass weighted average.

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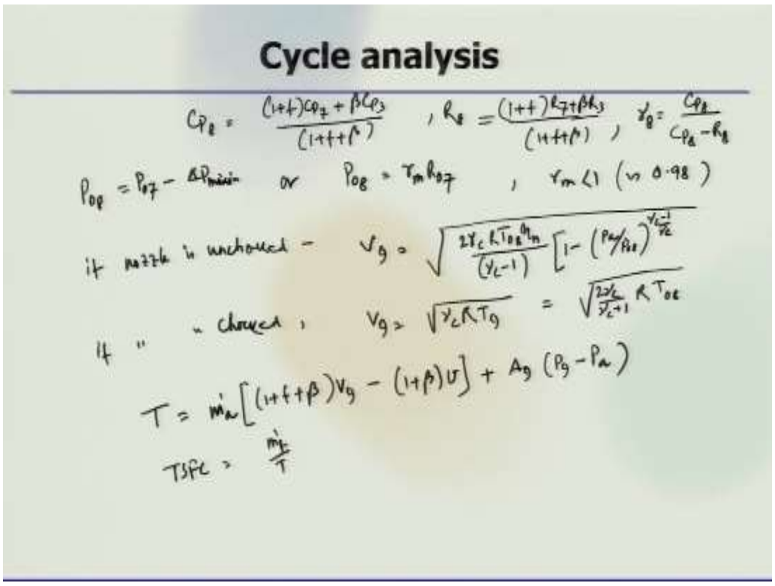

What we get

$$C_{P8} = \frac{(1+f)C_{P7} + \beta C_{P3}}{(1+f+\beta)}$$

Similarly,

$$R_8 = \frac{(1+f)R_7 + \beta R_3}{(1+f+\beta)}$$

and

$$\gamma_8 = \frac{C_{P8}}{C_{P8} - R_8}$$

Now considering the real gas of mixing where normally the losses are encounter and the pressure drop is associated with the mixing process and such pressure losses are either given or as a value of delta P mixing or as a ratio in the mixing process.

So then what we can write

$$p_{08} = p_{07} - \Delta p_{mixing}$$

or we can write

$$p_{08} = r_m * p_{07}$$

where r_m is less than 1. Typical values are around 0.98 something like that so that rm is the mixing ratio of the mixing process. Now we can check the nozzle choking condition so we have already mentioned so many times so that the nozzle is choked or not if so we have to look at the critical pressure nozzle is unchoked.

Then the exit velocity at

$$V_9 = \sqrt{\frac{2\gamma_c R T_{08}}{\gamma_c - 1}\left[1 - \left(\frac{p_a}{p_{08}}\right)\right]^{\frac{\gamma_c - 1}{\gamma_c}}}$$

and if nozzle is choked then V_9 is quite straight forward this would be

$$V_9 = \sqrt{\gamma_c R T_9} = \sqrt{\frac{2\gamma_c R T_{08}}{\gamma_c + 1}}$$

and equivalent thrust force which is given as

$$T = \dot{m}_a[(1 + f + \beta)V_9 - (1 + \beta)U] + A_9(p_9 - p_a)$$

So, that is what happens what you get and then also we can find out

$$TSFC = \frac{\dot{m}_f}{T} = \frac{f}{T/\dot{m}_a}$$

So that is how one has to look at the mixed flow engine. Now another one could be this same engine where we can use for the sort of an with afterburner.

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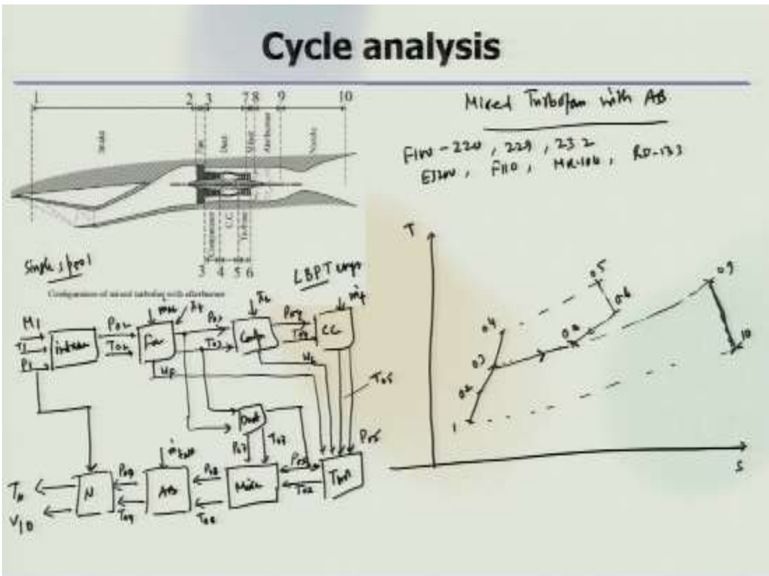

So this is another engine where you have mixed turbofan with afterburner there. So this I mean military aircraft are powered by low bypass ratio turbofan typically with afterburner so that is one of the important condition for the military application you need certain acceleration, maneuvering and all such thing. So if you look at this diagram this is starting from the intake this is fan then this is a fan duct you have the core of the engine where compressor, combustor turbine.

Then there is a mixing and after mixing there is afterburner which is sitting there before it is allowed to pass through the nozzle. So, which means whenever we have looked at so far before unmixed turbofan when we looked at previously in unmixed turbofan you have afterburner sitting after the turbine, but now in the mixed where the hot and cold gases are mixed then the afterburner is used to energize the incoming hot gases here and then pass through the nozzle.

And then there are multiple like this kind of things like pattern which we have sort of series which for example let us say they have F100 to 220 then they have F100 to 229, they have 232 different series then Eurojet has EJ200, GE has F110, MK 104, RD 133. So there are different engine manufacturer, but one thing by this time it should be clear there are only few engine manufacturer.

Because whenever we pull off this information every time when you look at this things that this when we talk about all this we have either Pratt & Whitney and General Electric which are US based company and then you have Rolls-Royce which is UK company and or the Russian engine like this. So there are only few engine manufacturers which actually produce engine.

And now this guy is essentially one can think about it is a forward fan mixed afterburning low bypass ratio so low bypass ratio turbofan engine. So this is a low bypass ratio turbofan engine. So quickly we can look at the block diagram of this one, the block diagram will give you an idea about like if I look at the block diagram how to do the analysis maybe we are not going to carry out the detail analysis because this would be pretty much similar.

But only thing once you have the TS diagram and the other stuff probably one can so 1, 2 then you have 2 to 3, 3 to 4 then 4 to you go to let us say 5 then you come to 6 then which will go to 9 then 6 comes to somewhere this is 8 and then 9 comes to this comes to 10. So that is the TS diagram and one can see the TS diagram and then so the other thing is that like the block diagram also.

So what will happen by looking at the TS diagram block diagram would be quite easy like you have intake where you get M_1, T_1 you get P_1 from intake you go to fan where you have P_{02} T_{02}

then you have $\dot{m}_{ac}$ which is cold then you have fan pressure ratio π_f now from fan it goes to sort of an P_{03} and T_{03} which goes to compressor pressure then there is a compressor pressure ratio.

Then from compressor you goes to combustion chamber this takes you P_{04} and T_{04} where you inject $\dot{m}_f$ Now from there it comes down to sort of a turbine so turbine it comes P_{05} and T_{05} and then also at the same time the fan it goes compressor from where this also goes that is W_c and also fan this is W_F. So this goes in then in between there could be here is the mixture.

So mixture it goes T_{06} and also some values and you have duct now duct get input from T_{03} and then duct so here we will just little bit we have P_{06} let us say T_{06} from duct also this goes and then here it goes T_{07} goes P_{07}. From mixture what comes out it goes to AB and that comes out P_{08} T_{08} and then you inject here $\dot{m}_{fab}$ afterburner finally it goes to nozzle where it enters P_{09} and this is T_{09} and you get T_{010} V_{10} and this goes here. So, that pretty much a block diagram that you can see and that probably so this also one can think this is a single spool so that is why single spool.

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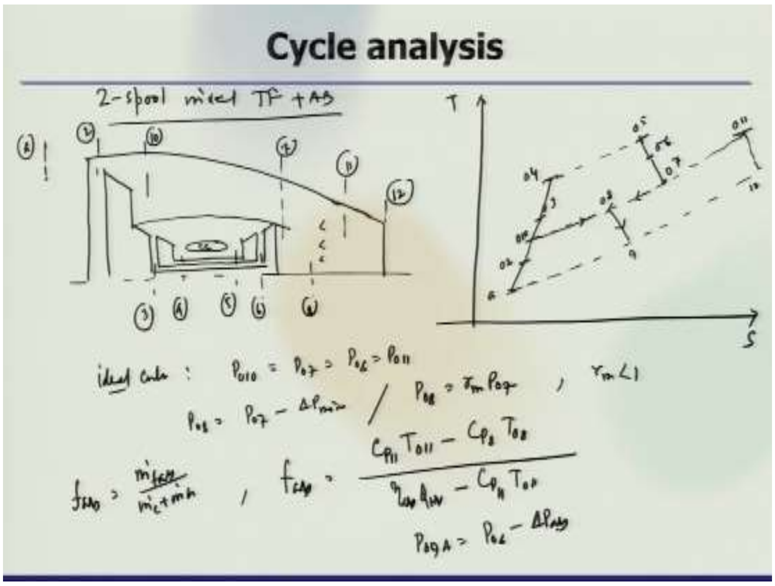

Now similarly if you look at a two spool then the diagram would look slightly different it is just let us say if a two spool mixed turbofan plus AB. So if you look at that so that would be like here is the casing then you have it so that goes so here is the combustion chamber and that connect and maybe this one slightly we can extend and this is where probably we have afterburner.

So this is station 1 and a then this could be 2 here is 3, 4, 5, 6 then this is 7, 8 then this is 10 afterburner it would be 11 finally it is 12. So that is how it looks like and similarly for this case the TS diagram would be can be drawn similarly or like this is starting a it goes to 2, 2 to 10 then 3, 4, 5 and 6 then 6 to 7 somewhere 8 and then this goes somewhere 11. So 8 it comes like 9 or it comes to 12.

So, this is how this diagram looks like same conditions necessary for next which we have already discussed. So same stands for ideal condition, ideal condition it would be P_{010} which would be P_{07}, P_{08} normally mixing process is associated with pressure loss which can be taken into consideration by delta p mixing and then or we can write

$$p_{08} = r_m * p_{07}$$

where r_m is less than 1.

So P_{01} is the total pressure at the outlet of the afterburner and outlet temperature would be T_{011} which is also probably known in advance. So because that maybe the maximum temperature which allows to have the engine because of the material consideration and but this could be quite hard than this engine and quickly doing the mass balance for afterburner, fuel air ratio would be

$$f_{ab} = \frac{\dot{m}_{fab}}{\dot{m}_c + \dot{m}_h}$$

So energy balance would give us

$$f_{ab} = \frac{(C_{P11}T_{011}) - C_{P8}T_{08}}{\eta_{ab}Q_{HV} - C_{P11}T_{011}}$$

$$p_{9A} = p_{0a} - \Delta p_{ab}$$

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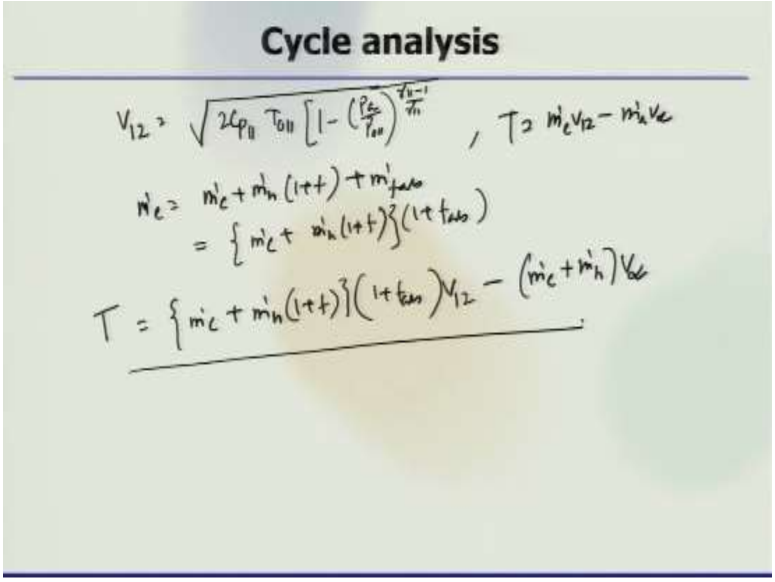

And so again the nozzle should be checked for this things and

$$V_{12} = \sqrt{2C_{P11}T_{011}\left[1-\left(\frac{p_a}{p_{08}}\right)\right]^{\frac{\gamma_{11}-1}{\gamma_{11}}}}$$

and thrust would be

$$T = \dot{m}_e V_{12} - \dot{m}_a V_\infty$$

where

$$\dot{m}_e = \dot{m}_c + \dot{m}_h(1+f) + \dot{m}_{fab}$$

$$\dot{m}_e = \{\dot{m}_c + \dot{m}_h(1+f)\} + (1+f_{ab})$$

So, the thrust force we can rewrite

$$T = \{\dot{m}_c + \dot{m}_h(1+f)\} + (1+f_{ab})V_{12} - (\dot{m}_c + \dot{m}_h)V_\infty$$

So also similarly for the two spool turbofan with afterburner can be calculated. So we will stop the discussion here and continue this discussion for other different kind of configuration in the next lecture.