Introduction to Airbreathing Propulsion
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Lecture – 14
Introduction to Gas Turbine Engines (Contd.,)

Okay! So we are looking at the different efficiency and performance parameter and we have looked at all this propulsion efficiency, thermal efficiency, propeller efficiency and overall efficiency for turbojet. Now the same thing we are going to look at how it varies for turbofan engine.

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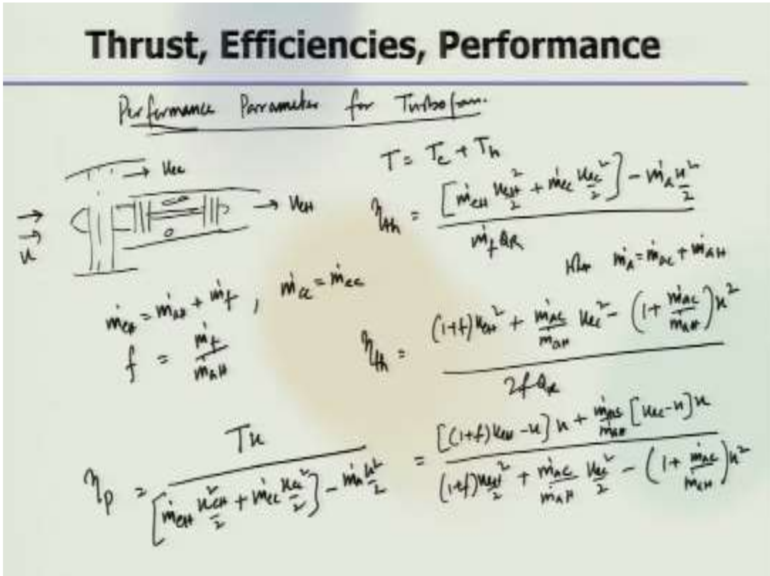

Now for turbofan we are going to derive those similar expression like show the parameters can be for turbofan. So, here as we recall the engine has two sections just getting it just to recall that. So then you have compressor then finally go through that. So these are hot exhaust, these are cold exhaust, this is u. So there are 2 contributing factors. One is the cold thrust other one is the hot thrust.

So, they contribute to each other and they both of them actually the total thrust component of the cold and the hot. So, here the thermal efficiency could be like

$$\eta_{th} = \frac{[\frac{\dot{m_{eh}} u_{eh}^2}{2} + \frac{\dot{m_{ec}} u_{ec}^2}{2}] - \frac{\dot{m_a} u_a^2}{2}}{\dot{m_f} Q_R}$$

$$\dot{m_a} = \dot{m_{ac}} + \dot{m_{ah}}$$

and we have

$$\dot{m}_{eh} = \dot{m}_{ah} + \dot{m}_f$$

$$\dot{m}_{ac} = \dot{m}_{ec}$$

So

$$f = \frac{\dot{m}_f}{\dot{m}_{ah}}$$

Now similarly the propulsion efficiency which is

$$\eta_{pr} = \frac{Tu}{\dot{m}_{eh}\frac{u_{eh}^2}{2} + \dot{m}_{ec}\frac{u_{ec}^2}{2} - \frac{\dot{m}_a u_a^2}{2}}$$

So we can have the propulsion efficiency and thermal efficiency in this expression.

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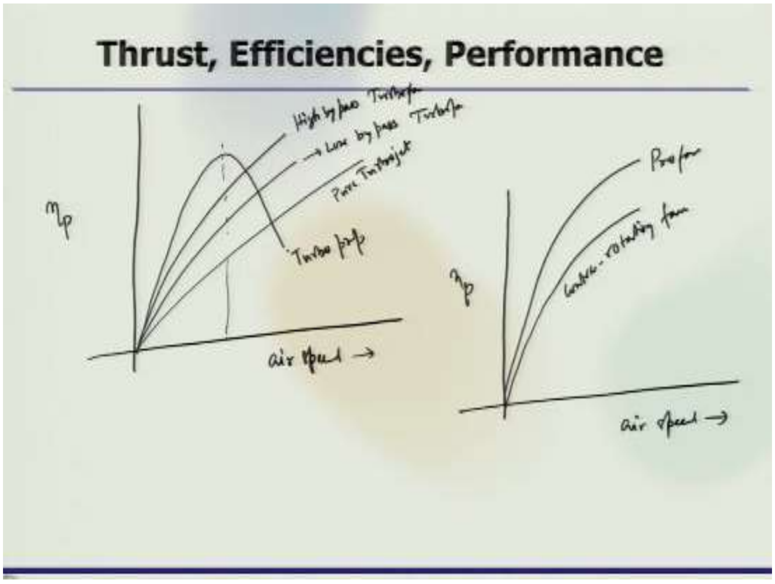

Now we can look at the curve like how let us say if we draw it with the air speed and this side propulsive efficiency then we have curve like so curve goes like that this is pure turbojet then we have this then we have this then we can have this is turboprop. This is low bypass, this is high bypass turbofan. So that gives you an idea how propulsion efficiency with the air speed that varies.

So, if you take an lower air speed then you can see that is what we have been always talking that at the low speed application turbo propeller engine is quite effective. You can see the propulsive efficiency is the maximum, but we increase the air speed this side then obviously the propulsion efficiency of the turboprop engine drops, but at the same time we have the turbofan and turbojet their efficiency goes up propulsion efficiency.

So another curve which may be interesting to just note again this is with air speed and this is propulsion efficiency. So this is for like and this is for propeller fan and this is contra rotating fan. So even their propulsive efficiency can be compared how this thing actually vary. Now what we can look at is with this kind of efficiency and other parameters.

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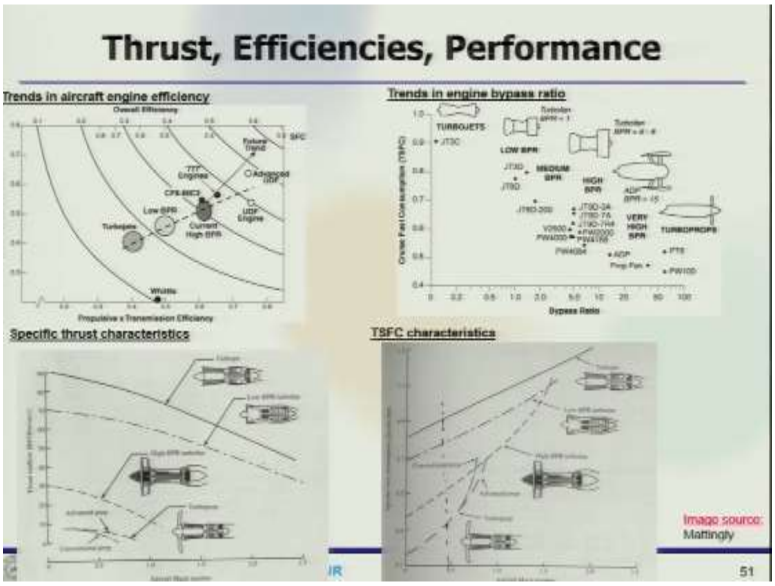

So we can really go to some particular trend. So, these are the some of the pictures which give you an idea like how this different kind of engines and what is there. So let us look at the first picture so this is the 4 thermal efficiency versus propulsion into transmission efficiency and you see this old whittle engine where they belong and this side is the overall efficiency and this also SFC.

So, this is where our turbojet then low bypass ratio turbofan then current bypass ratio turbofan which are there then we have future trend how things are going to be advanced in this direction and other one which is there is depending on the bypass ratio this is the different factors of the bypass ratio and this is the fuel consumption rate or TSFC thrust specific fuel consumption this is where turbojet lies.

This is on top then turbofan with bypass ratio 1 then low bypass ratio your medium bypass ratio, then high bypass ratio, turbo propeller and these are the different example of all this different category of engines where they belong and how their performance parameter which I just try to draw schematically. Now, another curve which would be interesting to see is the specific thrust characteristics where again this is the aircraft mach number.

And you can see how the trend looks like the trend is you have turboprop here then you go to high bypass ratio turbofan, this is low bypass ratio turbofan and that is where that turbojet belongs to and that is the one which finally takes to the TSFC characteristics that is your specific fuel consumption rate with the aircraft mach number. Again, this bottom curve is turboprop, then you have high bypass ratio turbofan, then you have low bypass ratio turbofan.

How that seen changing and in between there is a small deviation for the turboprop which is the conventional propeller engine and this is where the turbojet. So, the interesting thing to note here let us say given a mach number if it is low subsonic range let us say we come here the TSFC is quite high for turbojet and then low bypass ratio and turbofan, but when I go to high mach number.

Then you can see this is what this is what low speed application turboprop is preferred and high speed application bypass ratio turbofan these are preferred and at the same time the other curves also kicks in. Now that will you give some idea about how this trends are.

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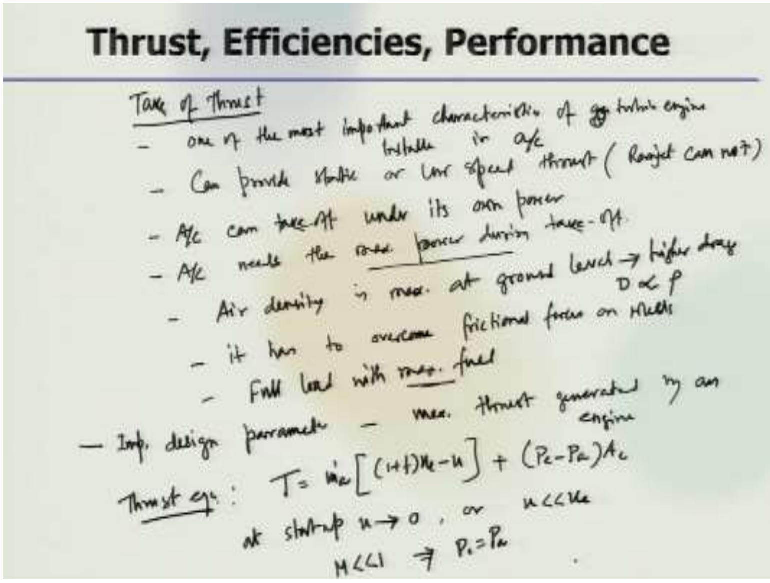

Now moving forward the important one is that we look at the take off thrust. Now, this is another important factor that actually affects the performance. So, this is as I said one of the most important characteristics, one of the most important characteristics of a gas turbine engine or of a turbine engine installed in aircraft. So, it can provide static or low speed thrust ramjet cannot.

So this take off thrust is very, very important because this can be only produced when we have this combination of compressor and turbine and such that, but it can provide static or low speed thrust. So, ramjet engine cannot do that so that is important restriction for ramjet engine. Now any aircraft can take off under its own power so that is which is essential requirement and at the same time during take-off aircraft needs the max power during take-off.

So, also this is important that take-off thrust is going to be the maximum thrust because this required during take-off and the take-off usually happens at the sea level where air density is also maximum at ground level and that leads to higher drag because this is proportional to density. So, the aircraft has to also overcome frictional forces on wheel. So it has to overcome frictional forces on wheel also full load with maximum fuel.

So that means the load is full load with max fuel that means when the aircraft is taking-off that time you have the maximum payload including the fuel weight which is also maximum. So this is an very, very important design parameter because this is the max thrust generated by an engine and that is what required during take-off. Now how that makes things different or how it affect let us see.

It is simple I will start with let us say thrust equation. So, that is

$$T = \dot{m}_a[(1+f)u_e - u] + (P_a - P_e)A_e$$

Now what happens that startup u goes to 0 or u is very, very smaller than ue. So which will lead to m would be quite small and that means Pe what is there that should be Pa that means the atmospheric condition.

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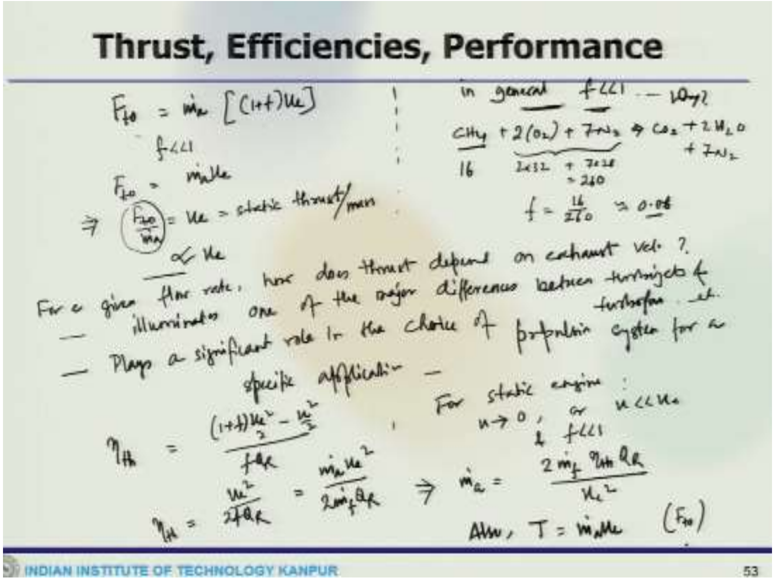

So with these conditions one can write the thrust which is going to be during take-off its equal to

$$F_{TO} = \dot{m}_a[(1+f)u_e]$$

and always we keep on saying so far whether instead that in general f is very, very small, but one can always say why or one can look at it. Just to justify that statement which we have been always talking that fuel air ratio would be always less. Let us say any hydrogen fuel you take let us take the simple one typically methane.

So what happens just look at the methane combustion so this is

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + 7N_2$$

So that is sort of an balanced equation then here fuel is 16 and if you look at this here which is this is 7 into 28 + this is 2 into 32 this would be roughly 260. Now the fuel air ratio would be 16 / 260 which is 0.06 and that is what we always say in general this engine is the fuel air ratio is quite small and that is an example.

Now you can take the other fuels like all this jet fuels or things are all hydrocarbon fuel which are of the similar category and you can have this. Now, let us coming back to this take-off thrust since f is small we can write take-off thrust is m dot a into ua which means to / m dot a is ue which is the static thrust per unit mass. Now this static thrust per unit mass this guy is directly proportional to exit or exhaust velocity that is what we can see.

But it would be interesting to also look at for a given flow rate how does thrust depend on exhaust velocity. So, that would give us an important aspect or this answer also this will also or this answer to this question also shed some light that one of the major differences between turbojet and turbofan. So, this plays a significant role in the choice of propulsion system for specific application that means this guy plays a significant role in the choice of propulsion system for a specific application.

Let us see how that happens. So, we have already derived the relationship for the thermal efficiency and the thermal efficiency is

$$\eta_{th} = \frac{[(1+f)\frac{u_a^2}{2} - \frac{u^2}{2}]}{fQ_R}$$

Now for static engine u goes to 0 or u is very, very smaller than ue and at the same time we have f is smaller than 1 then we can write this thermal efficiency as

$$\eta_{th} = \frac{u_e^2}{2fQ_R}$$

which is equivalent to writing

$$\eta_{th} = \frac{\dot{m}_a u_e^2}{2\dot{m}_f Q_R}$$

Now from here what we get that

$$\dot{m}_a = \frac{2\dot{m}_f \eta_{th} Q_R}{u_e^2}$$

and also we know thrust is m dot a that take-off thrust that we have got m dot a which is the take-off thrust essentially ue.

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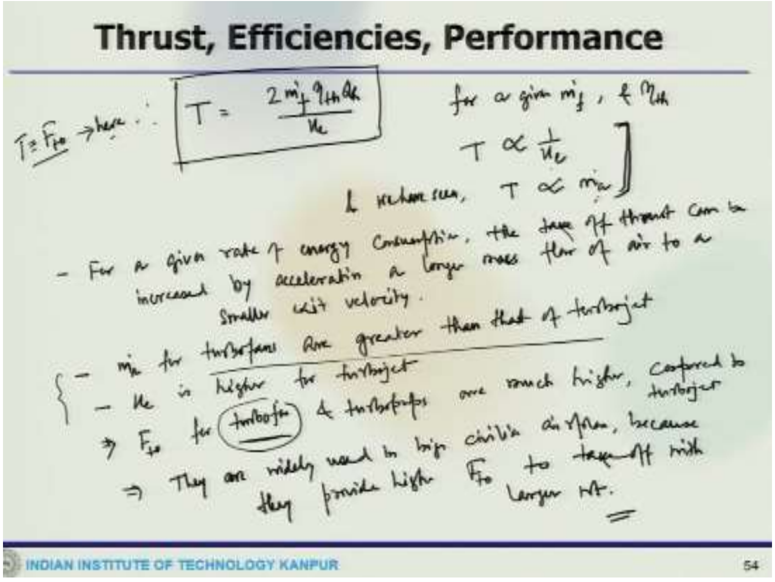

So, we can write this is

$$T = \frac{2\dot{m}_f \eta_{th} Q_R}{u_e}$$

So that is what a important finding so this one can say this thrust is here we mean to say that take-off thrust here. So this is here it is take-off thrust. Now, what we can see for a given fuel flow rate and thermal efficiency this take-off thrust would be inversely proportional to ue and we have seen thrust is also proportional to $\dot{m}_a$.

So which clearly says that for a given rate of energy consumption the take-off thrust can be increased by accelerating a longer mass flow of air to a smaller exit velocity. So, this is very important that for a given rate of energy consumption the take-off thrust can be increased by accelerating a longer mass flow rate of air to a smaller exit velocity that means if you club these two clause together either we can increase $\dot{m}_a$

Once we do that the take-off thrust could be increased or so with the larger mass flow rate and smaller exit velocity that means when the engine is starting off during taking off the aircraft this guy may be small, but with larger mass flow rate it can be increased the take-off thrust can be higher and m dot a for turbofan are greater than that of turbojet. So, now you can see why this recent development is very much a common choice of using turbofan engine.

But this can provide higher take-off thrust, but ue is higher or is much higher for turbojet. Now, combining this one can think about this take-off thrust for turbofan and turboprop are much higher that is compared to turbojet. So that is why you can see why as I said turbofan engines are preferred. So they are widely used in big civilian airplanes because they provide higher take-off thrust to take-off with larger weight.

And that is one of the primary reason why these days all the development which one can see even when you have seen the recent development and the kind of engines what we have discussed during the introduction or introductory lecture this turbofan is more and more popular, but with a different blends of bypass ratio. Sometimes it is a low bypass ratio, sometimes it is a high bypass ratio it depends on the application.

Depends on the user choice so that is how the development is going on and turbofan is more and more popular or gaining popularity or other use in the recent development. So we will look at the other aspect in the next lecture.