Indian Institute of Technology Madras
Presents

NPTEL
NATIONAL PROGRAMME ON TECHNNOLOGY ENHANCED LEARNING

Aerospace Propulsion
Air breathing Engines –
Turboprop & Turbofan

Lecture 4

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Last class we had stopped at turbojet engines with after burner and water methanol injection, we understood how these things work right, and why thrust augmentation is needed. Now let us look at where all are these turbojets currently being applied okay.

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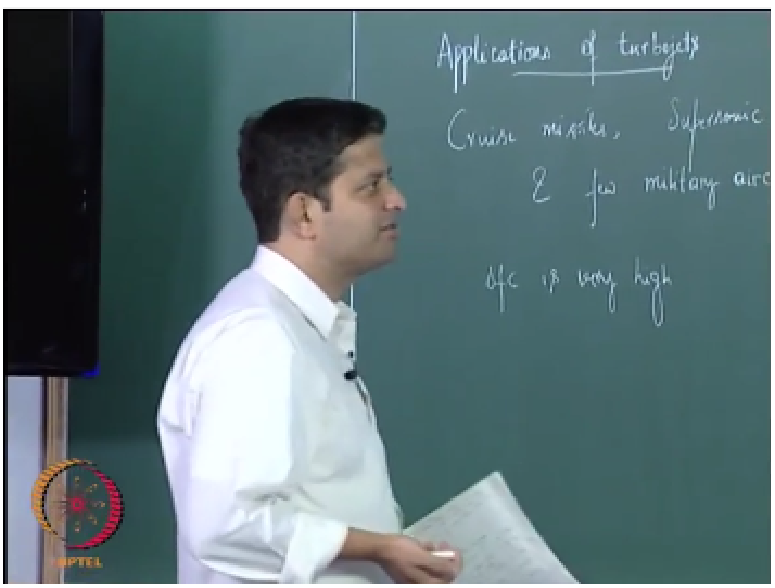

Where do you think they are applied, any idea know that they are not so much in use and fighter aircrafts today very, very few fighter aircrafts use it so they are basically used for cruise missiles and then supersonic transport and the supersonic transport was the Concorde that was using it okay, and very few military aircrafts use it most military aircrafts currently use a low-bypass turbofan we will look at what a low-bypass turbofan is and why they use that a little later, okay.

Now we have understood how thrust is developed right, in a turbojet and have derived that equation all that we have done. Now what is the Mach number range of a turbojet, what range of speeds can it worked. Any idea, it grew up to 3 sometime Mach number of 3 and it can go from 0 to Mach number 3, altitude it is known to go to very high altitudes, altitude is not a problem the Mach number is not a problem.

So we should have stopped here technically right, it fulfills all our requirements of flying faster and higher, so why are there other engines okay. One of the key things here is that the specific fuel consumption of turbojets is very high and therefore people started to look at whether there can be an alternative in terms of reduction of SFC, okay. Now the next generation of aircraft engines was the turboprop engines.

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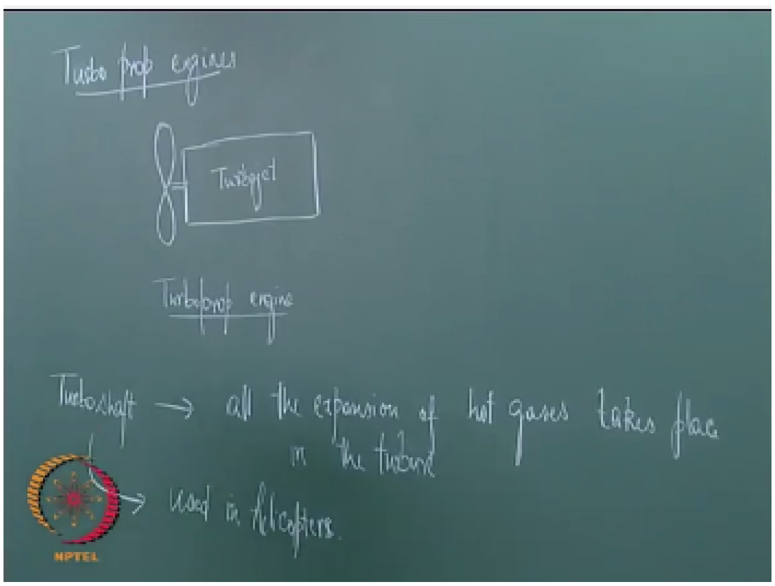

The idea behind a turboprop is very simple people had piston engine plus propeller earlier now they had a turbojet, now in a turbojet the turbine produces sufficient power to just run the compressor and there is scope for extraction of more work from the fluid which we would in a turbojet allowed to go through the nozzle so that you get the required thrust. Now what you can also do is not let it go through the nozzle not let it expand through the nozzle.

But take out as much work as you can in the turbine itself okay, then you have a lot more of shaft power which you can use similar to what a piston engine was doing and connect a propeller in front okay, that is what is the turboprop engine. So if you look at it if you look at the turbojet engine as a box let us say this is the turbojet engine then you attach a propeller in front you get here turboprop engine, okay. That is the essential idea of a turboprop engine and if you take a look at this figure here you will see that.

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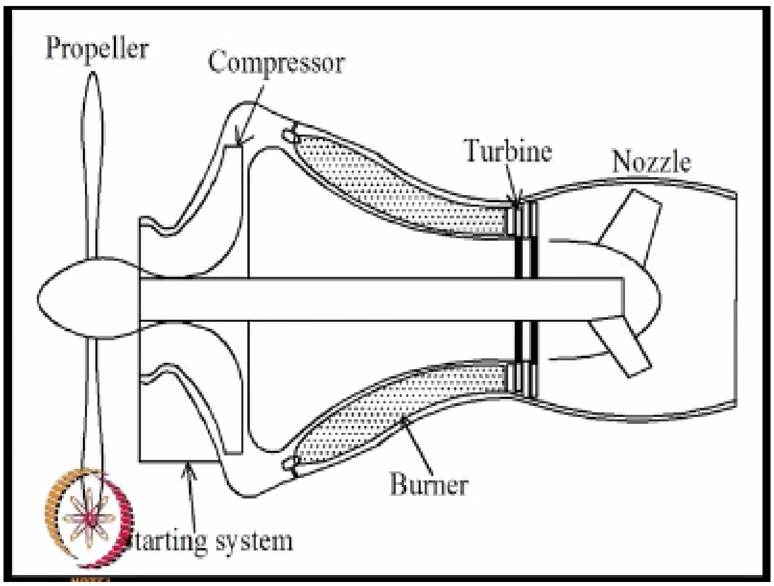

This entire thing is a turbojet engine right, with a centrifugal compressor and you have a turbojet engine, now if you attach propeller to in front of it then it becomes a turboprop engine the power to drive both the compressor as well as the propeller should come now from the turbine that is you should extract sufficient work out of the fluid so that it runs both the compressor and the propeller, okay. So that is a turboprop engine it is possible in a turboprop engine to distribute the power obtained from the nozzle and the power of paint from the propeller optimally okay, but if all the power is supplied only to the propeller then it becomes what is known as a turbo shaft engine.

All the expansion of hot gases then it becomes a turbo shaft engine, turbo shaft engines are used in helicopters right, so these are now the performance of this turboprop engine is in between that of at the turbojet and a piston engine plus propeller okay.

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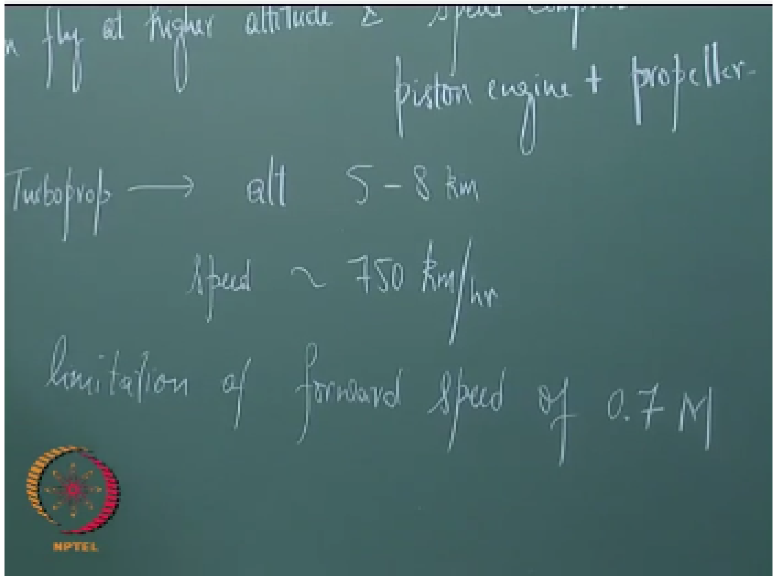

So it is more, more fuel-efficient than turbojets and it can fly at higher altitude and speed compared to a piston engine plus propeller. Typical altitudes H which turboprops can fly up 5 to 8 kilometers and speed as around750 kilometers per hour okay. Yeah, okay, good see let me look at the thrust equation that we derived in the last class.

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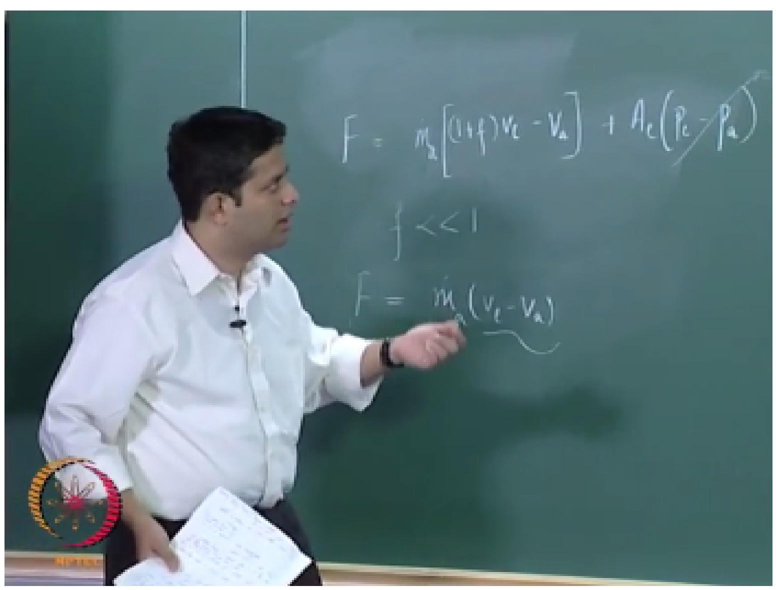

Now if you remember our first equation right, this was a thrust equation and as I said this portion is larger compared to this portion this portion is a very small point. Now if you look at this portion you can look at it as mass flow rate into velocity differential, if we assume f to be very small compared to 1, f is typically around 0.3, 0.3 to 0.1 so if you assume this then you can rewrite and if you assume that exit pressure is equal to ambient pressure then this goes to 0 and you can rewrite your thrust equation as.

So mass flow rate into velocity differential right, between the flight velocity to the exit velocity of the jet right, there is our thrust is obtained. Now there are two ways of getting the same thrust here, one is if you get the same trust by increasing this part right, that is one way or you can get to the same thrust by increasing the mass flow rate through the engine okay.

Now what is done in a turbojet is that you increase the velocity differential ve is much greater than va and therefore you get a high thrust and you can get the same thrust by having a smaller ve-va, but a larger mass flow rate. In a few classes from now we will be showing why if ve-va is large you will get a lower efficiency we have to discuss something known as propulsive efficiency which we will talk about a little later in the course.
And then I will be able to show you why if this is large you will get a lower efficiency okay, so what is done in a turboprop engine is to get to the same thrust you are now pushing through a larger flow-rate but with a smaller velocity increment. Remember the velocity increment is something similar to what we discussed in piston engine plus propeller.

So you have va and ve here and this differential is not large but a large mass flow rate is passing through the fan and therefore you get the high thrust okay, and not through the large portion of this therefore it becomes more efficient. But turboprop engines also have a limitation, the limitation is they cannot go beyond a forward speed of something around 0.7 Mach number.

Although there is more efficient there is a limitation that you cannot go beyond 0.7 Mach number. Now this limitation comes about because of what happens at the phantom now you want it more to be more efficient so you want a larger propeller so that you pass through a larger mass flow rate through it, right.

So if you increase the diameter now you are increasing the diameter and the RPM that it rotates that is typically around 2500 rpm the propeller rotates it, if you are increasing the diameter then what happens to the speed at the tip the rotational speed that also increases right. So in addition to a forward component it has two components one va and one is u.

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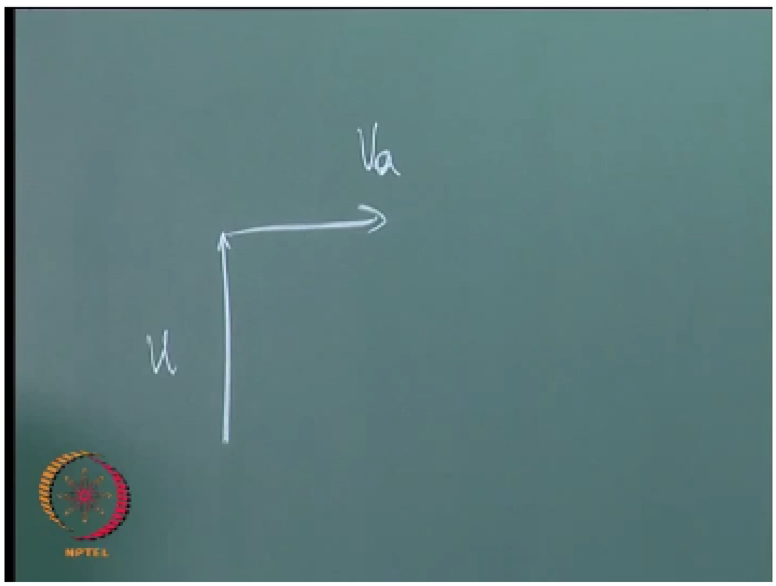

So the combination of these two which is the actual velocity that the blade tip sees might exceed Mach number 1 when the forward speeds are around somewhere around 0.7okay, when that happens there is a shock structure that gets formed at the propeller tip and that reduces the efficiency of the propeller very much, and therefore you will not be able to get the required thrust okay.

So therefore you cannot operate it beyond this forward speed so what is done is you do not want to reduce this diameter because then your mass flow rate through it will be small, so there is a limitation that you cannot go beyond 0.7 Mach number okay. Now we had taken a look at how the piston engine plus propeller performs like if you remember in the previous class two classes back I looked at what are all the numbers SFC and other things right.

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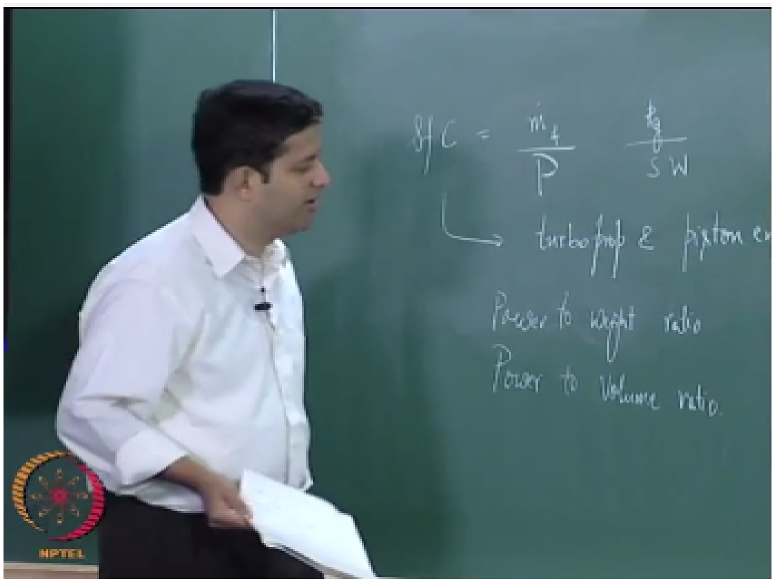

If you remember what is the definition of SFC we had defined SFC for a turbojet engine, for a turboprop engine it is slightly different it is m0f/P per unit power that is produced okay, so the unit will be what will be the unit if you have this in watts what will be the unit, what is watt per second so either you can leave it as kg/sw or you can put it as okay. So this is the SFC for definition for okay, the essential idea is we want to compare the power that is developed by the engine and not look at what is the final thrust that is delivered.

The final thrust that is delivered is a function of the propeller characteristics, so we would want to take it out and look at what is the SFC without the propeller being involved okay, and in the last class I had defined what is SFC for a turbojet engine okay. Now in addition it is the shaft power it is not the power generated by the turbine but it has the power that is available that is power generated by the turbine -the power consumed by the compressor and what is available for doing useful work, okay.

Now there are also other parameters that we looked at that is power to weight ratio and okay, now what does power to weight ratio tell you it should be higher or lower, what is desirable if it is higher than the weight of the engine that you need to carry to deliver the same power will be smaller okay, and power to volume is it tells you what is the size and therefore a higher value will be desirable because it reduces drag okay, fine. Now let us look at the comparative stats between a turboprop engine and a piston engine plus propeller.

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Comparison of Piston engine + propeller and turboprop

Engine	Power, P kW	Mass, M kg	sfc kg/kWhr	P/M kW/kg	P/Vol. MW/m³
AI -14 R, Poland	242	245	0.36	0.98	0.31
P & W R-4360 Wasp (28 cyl)	2600	1579	-----	1.83	----
Lycoming R-7755 (36 cyl)	3730	2745	0.43	1.36	----
Allison T -53 A	1044	250	0.58	4.2	3.3
[illegible] 34	1976	263	0.62	7.5	5.8
[illegible] Tyne	4985	1034	0.58	4.8	1.9

What I have put together in this table is the ones in the black our piston engine plus propeller and the ones in red are turboprop, now notice that for the same power level we can compare two 2600 and 2000 nearly the same power level look at the mass of the engine that is required it is a dramatic reduction right, and therefore consequently you have the power to weight ratio of the power to mass ratio is something like 7.5 for a turboprop whereas it is around 2 for a piston engine plus propeller.

So it makes this power-to-weight it reduce the weight of the engine dramatically, now if you look at power two volume right, it is a very small number for piston engine plus propeller around 0.3 whereas it is around 6 maximum in the case of turboprop engines. So it not only reduces the weight of the engine it also reduces the size of the engine.

So power to weight and power volume of turboprop are much more superior to that of piston engine plus propeller and that is the reason why you would not find piston engine plus propeller operating in a large number of application these days they are very much restricted to either a unmanned aircraft or two to four see aircrafts and agricultural aircrafts okay.

And most of the large passenger applications has been taken over by turboprops, because the drag is less as well as the weight is much more smaller, why does this, how does this happen, why is it that you have seen this we go from one to the other magic why do you think is this happening. The part of it is correct, the other part that you are missing is if you remember our equation that we derived for the power of the piston engine plus propeller.

You will discover that it is directly proportional to the RPM right, and I told you that if you look at Enfield Bullet and the current day pulsar other vehicles you will find that the RPM is higher and therefore the power to weight will be much more right, and a very similar thing happens here the RPMs of gas turbine engines are much higher than RPMs of piston engine plus propeller okay.

It is typically in the range of 20,000 and if you go for a smaller micro turbine that will be in the few lakh RPMs to go to fuel a car peels very large gas device operate at a reasonable rpm of around 10,000, so it is much larger than typical IC engine RPMs and therefore you find that these two are smaller. In addition it is a larger mass flow rate that is going through the engines right, and you can add more fuel and therefore you find this advantage being there.

And as I said because of this phenomenal advantage the IC engine or the piston engine plus propeller lost out and you are only left with turboprops and turbo props have an application.

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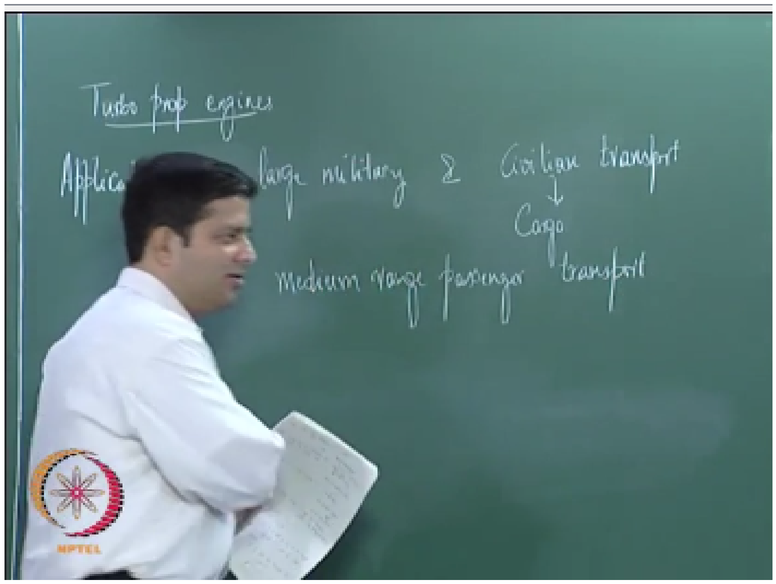

You have turboprop engines being used in large military and civilian transport is mostly restricted to cargo, large military aircrafts anything comes to mind India recently acquired something from the US, C-130 right, they acquired very recently a lot the or number of aircrafts something similar is Antonov very large aircrafts for military transport and civilian cargo transport only because if you are looking at cargo it does not matter to cargo that it has to sit for a large number of hours in the plane.

But if you are looking at passenger transport because you have this restriction on forward speed of 0.7 the time taken will be much larger for longer haul flights right. So therefore you tend to use turboprop engine in medium range passenger transport, so you would not find it across continents but inside countries and side continents you will find this for passenger transport right, okay.

Now the next generation of engines came out of turboprops primarily to address this limitation this was the limitation with turboprops SFC wise it is very good but I cannot go beyond 0.7 Mach number, so we want to have the best of both words can we do with good SFC as well as go to higher Mach numbers what was available was only turbojets at that time which was very high SFC. So the next generation of engines that came about was what is known as turbofan engines.

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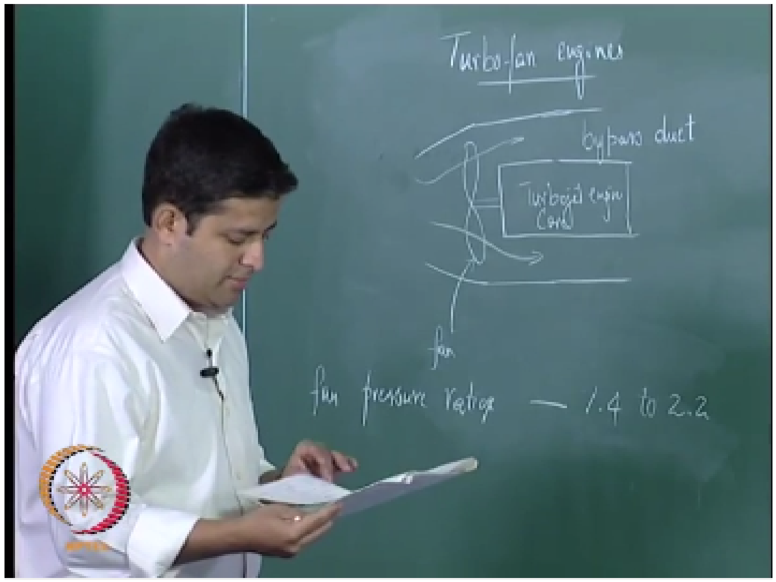

Now what was the problem with turboprop engines it was only 0.7 Mach number and that restriction was because at the blade tip right, now if we assume this is this box is the basic turbojet engine at and this was a turboprop engine the trouble was that because it is rotating at high RPMs and you have a large diameter at the blade tip the Mach number was exceeding 1 when the forward speeds was 0.7.

So the idea was why not reduce forward speeds ahead of this fan and a simple way to do it is put a diffuser in front of it right, if you put a diffuser in front of it what happens is irrespective of the flight Mach number you can control what is the flow speed upstream of the propeller or the fan right, so that is the essential idea of a turbofan engine.

So you have a part of the flow that is going through the fan and going through the, this is known as the bypassed duct and this is known as the core. So you have one part of the flow that is going through the core and the remaining going through the bypass duct okay.

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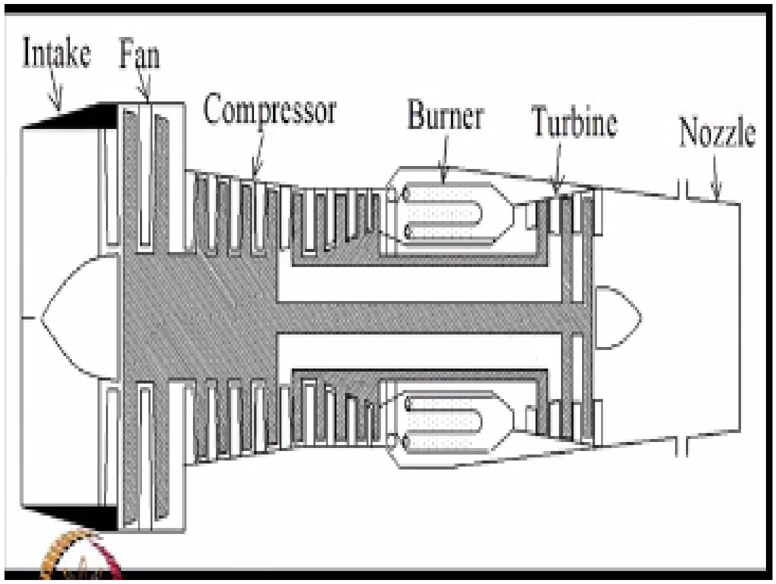

And if you look at this figure here you have what is a turbofan engine notice that you have an intake upstream of this and you have fan blades that are mounted on the same shaft as the turbine blades and the lows low-pressure compressor and the high-pressure compressor stages are mounted on a different shaft that is connected to the high pressure turbine here, right.

So the advantage with this kind of an engine it is called to spool engine because there are two shafts concentric shafts the advantage of this to spool engine is you can control the RPM at which you rotate different parts of the compressor okay, the low speed compressor can be operated at a lower rpm and the high speed compressor are the high-pressure compressor can be operated at a higher rpm, okay.

And that is the advantage of this and you have this fan here and there is a nozzle that and the flow goes out through this essentially this is something similar to the concept that we discussed earlier that thrusts large thrust can be obtained either with an increase in mass flow rate or an increase in velocity differential, what is done here is again large you know the mass flow rate goes through the fan and that velocity differential is very small there right, is more like a propeller and therefore the velocity differential is small so you get better performance.
Typically the fine pressure ratios are around 1.4 to 2.2 and with this arrangement you can go upto very high Mach numbers right, and still obtain the same with a lower SFC compared to a turbojet engine okay, and which is why it turbo Jets are hardly being used in any military aircrafts as well as civilian aircrafts right. If you look at civilian aircrafts I said earlier in the class that they mostly use it turbofan engine this is the reason.

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Now you can define a parameter called α which is known as bypass ratio α is equal to air passing through to the air passing through four-engine okay, so what is α for a turbojet engine plane turbojet engine there is no bypass duck right as I have shown here this is the bypass duct apart of the flow passes through the bypass that part of it flows through the core engine, core engine is still the turbojet engine, right.

If it is only a plain turbojet there is no flow passing through the bypass that and therefore α=0 for turbojet engines. Now you might ask me why is that you still insist that velocities are very small velocity differential is very small right, large mass flow rate with a smaller velocity differential is what I said you can have this nozzle also choke the pressure ratios allow you for that and yet I say that this is so.

The reason is if you look at this flow that is going through the bypass there is no heat addition anywhere right, and therefore the temperatures of the gases is lower so if it is choked even then we know that right so if the temperatures are lower than the velocities will also be lower a large portion of the flow is going through with a lower velocity a small portion of the flow is going through with a larger velocity overall you still have a very low velocity differential and that is how this produces higher SSE, okay.

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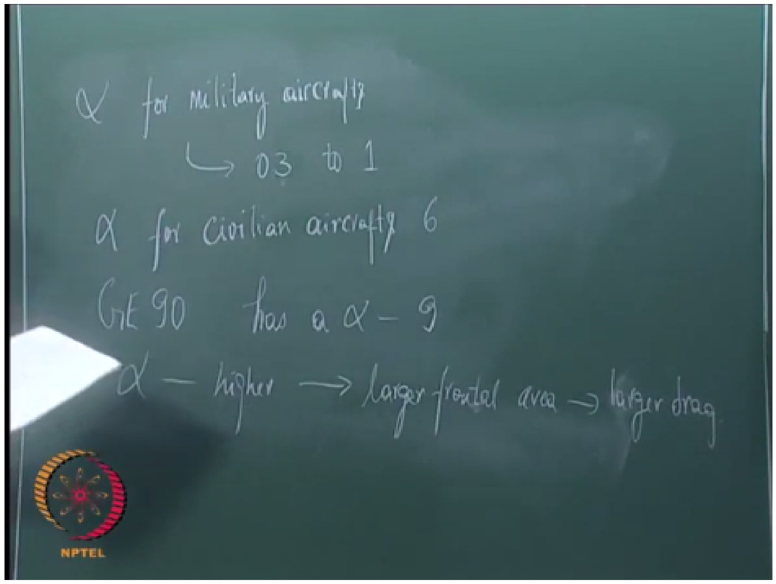

And typically α for military aircrafts will it be large or small α values for military aircraft okay, you are right, if you look at any military aircraft most military aircraft do not have their engines on the wings their engines are fitted into the body they are in the body itself right, because you do not want a large drag there are civilian aircrafts you will hardly find anything engine being fitted to the body engine is always outside okay.

So military aircrafts the engine is fitted into the body and you would like a smaller α because that will mean smaller frontal area also okay, so typical values are between 0.3 to 1 and α for civilian aircrafts is around six you can use a large α here okay, because the engines are no longer fitted onto the body its outside and the typical Mach number that some of these civilian transport aircrafts look at is around 0.8 to 0.85 they are not very high Mach numbers they do not go beyond the speed of sound okay.

So therefore you can look at a large value of α in fact GE uses even larger value of α, G engines go for typically GE90 engines as a α of around 9 it is very large, the reason they gave for this is that if you look at the drag component of the engine or the nasal drag as it is called and the drag component coming from the main body of the aircraft the drag component coming from the nasal is very, very small compared to the main body of the aircraft okay.

And they say that it is only in the second digit that it matters so you can go in for a larger frontal area here right, α increasing means you are going in for a larger frontal area they say if you increase α you are going to increase you are going to decrease SEC right. So therefore that is the advantage that they are looking at all those frontal areas increased dry is increased they say it is not too much compared to the overall drag whereas the advantage that you get in terms of SSE is much, much more.

So they go in for this α of around 9, so what we need to remember is α higher means larger frontal area and larger drag the same like we are fitting as simple fan in front of the turbojet if we remove that fan we run that turbojet is turbo jet has more trustful time. When we work out some more details I will be able to show that fan will have much larger thrust for the same if you look at for the same fuel that is consumed same amount of fuel that is consumed but the turbofan will have a larger thrust which is which will be obvious in terms of SEC.

So if you look at the data that I put together here in addition to what we hire in turbojets there is another additional parameter.

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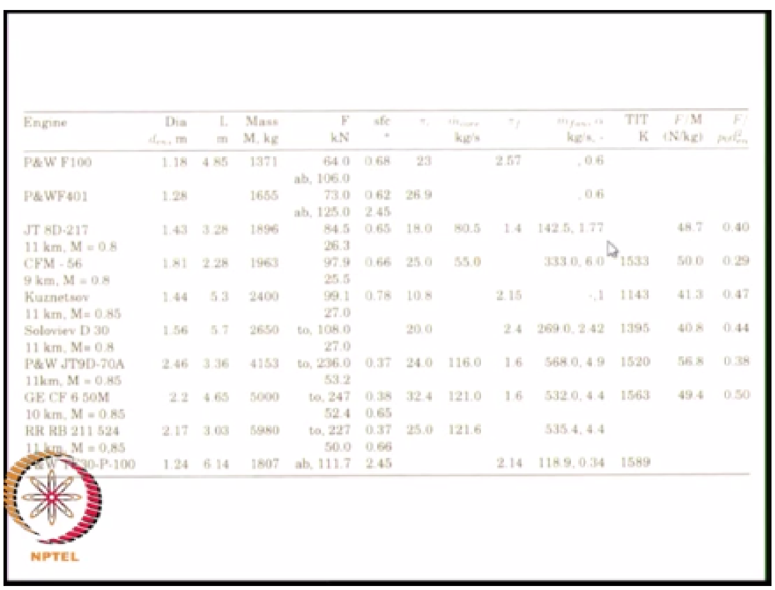

Engine	Dia d_{in}, m	L m	Mass M, kg	F kN	sfc *	π_c	$\dot{m}_{core}$ kg/s	π_f	$\dot{m}_{fan}$, α kg/s, -	TIT K	F/M (N/kg)	F/ [illegible]
P&W F100	1.18	4.85	1371	64.0	0.68	23		2.57	, 0.6			
				ab, 106.0								
P&WF401	1.28		1655	73.0	0.62	26.9			, 0.6			
				ab, 125.0	2.45							
JT 8D-217	1.43	3.28	1896	84.5	0.65	18.0	80.5	1.4	142.5, 1.77		48.7	0.40
11 km, M = 0.8				26.3								
CFM - 56	1.81	2.28	1963	97.9	0.66	25.0	55.0		333.0, 6.0	1533	50.0	0.29
9 km, M = 0.8				25.5								
Kuznetsov	1.44	5.3	2400	99.1	0.78	10.8		2.15	-,1	1143	41.3	0.47
11 km, M= 0.85				27.0								
Soloviev D 30	1.56	5.7	2650	to, 108.0		20.0		2.4	269.0, 2.42	1395	40.8	0.44
11 km, M= 0.8				27.0								
P&W JT9D-70A	2.46	3.36	4153	to, 236.0	0.37	24.0	116.0	1.6	568.0, 4.9	1520	56.8	0.38
11km, M = 0.85				53.2								
GE CF 6 50M	2.2	4.65	5000	to, 247	0.38	32.4	121.0	1.6	532.0, 4.4	1563	49.4	0.50
10 km, M = 0.85				52.4	0.65							
RR RB 211 524	2.17	3.03	5980	to, 227	0.37	25.0	121.6		535.4, 4.4			
11 km, M = 0.85				50.0	0.66							
[illegible]30-P-100	1.24	6.14	1807	ab, 111.7	2.45			2.14	118.9, 0.34	1589		

α coming in here right this is α and you see that α ranges between 4.9 to 2.4 to even smaller, smaller ones are for military aircrafts okay. There is an additional advantage in a military aircraft military aircrafts do not want to use turbojets because there is a other advantage that you can get with turbofan low-bypass turbofan any idea what that is. No. Yes, that is not a lot of it there is another advantage that is yeah that is a byproduct I would say more to do with propulsion let me tell you that.

The advantages look at this if you in most civil and engines you do not mix the two streams right whereas in a military aircraft you can mix the two streams and pass it through the same nozzle okay, what does that mean you additional air that is coming in into the after burner right, and that additional air you can add additional fuel and burn it, so the increase in the after burner thrust that you can get with the afterburner on is much more with a low-bypass turbofan and that is a significant advantage.

In a military aircraft you would want this you would want a large ratio of thrust when the afterburner is on to when it is not on, so and therefore military aircrafts have been tending to use a low bypass ratio turbofan for this reason also, okay. Now coming back to this table here if you look at all the arrangements the top few are military aircrafts and the bottom ones are civilian aircrafts GECM60 Pratt & Whitney engines okay, and this is the Russian engine notice that SFC here is different from the SFC that you saw in terms in the with regards to turbojet okay, and if you compare SFCs.

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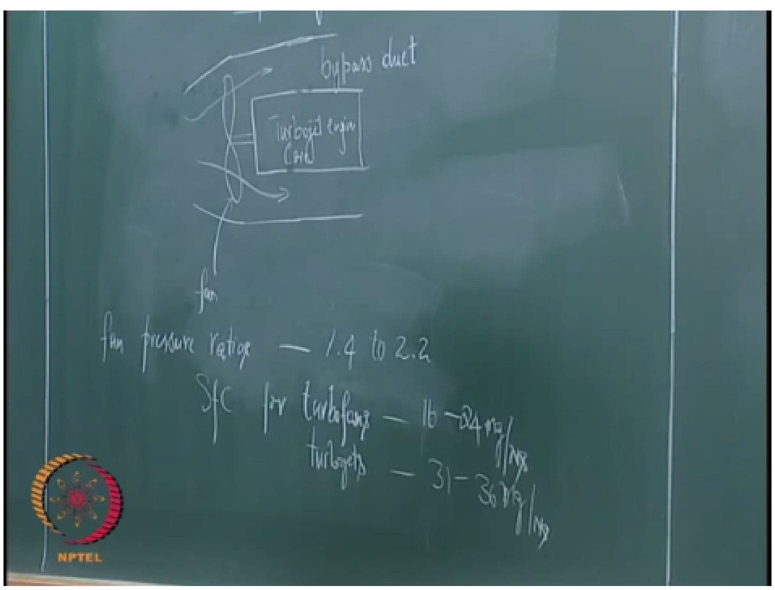

Fans are typically between 16 to 24 N/sec whereas it was around 30, 30 what was it 31 to 36 milligrams for the budgets so there is a difference in SFC it is almost half the SFC that you get with the budgets. And therefore it is quite obvious that you see these in civilian aircrafts more and the other advantage that I talked about for its use in military aircraft is that you can get a higher afterburner thrust, okay.

But you would also probably notice here the thrust to weight ratio would be lower compared to a turbojet engine right, and so also the thrust to volume it is a larger volume larger, larger frontal area casts so the thrust to volume and the thrust to weight are different from the turbojet engine it is larger than turbojet engine okay, and what are the applications of this,

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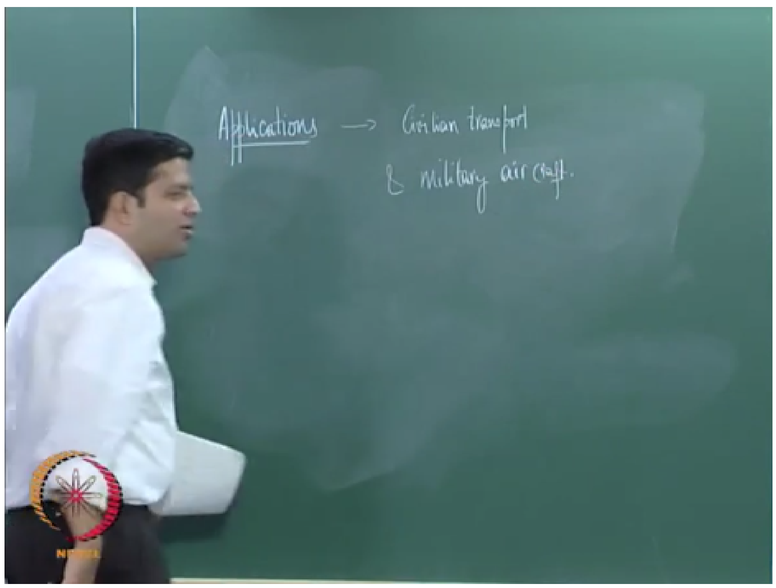

Where do you think these are applied civil in civilian transport and okay, we stop here and continue in the next class. In the next class we will look at water ramjets and how did they come about and further go into what our scramjet, okay, thank you.

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