Gas Dynamics and Propulsion
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Lecture - 30
Components of the Gas Turbine Engine

In the last class, we look at an ordinary nozzle for a turbojet engine and we saw how it operated in thrust reverse mode.

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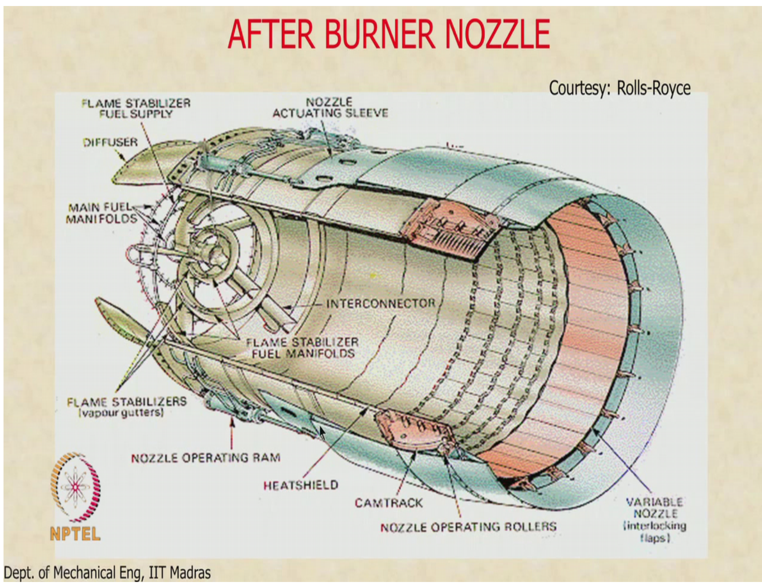

Today, we will start our lecture by looking at the nozzle for and after burner, the nozzle for the after burner has to be little bit more special because it has to accomplish in addition to the 2 things that we talked about, for example we said that the purpose of a nozzle is to produce thrust and also it must be used for thrust reversing. Now an after burner nozzle will not have the capability to have thrust reversing, so it will produce thrust.

But in addition, it must also be able to operate with the after burner on, so the nozzle is somewhat specialized and you see from here the nozzle is longer because there is a constant area duct where the inject fuel, so you can see the fuel manifold so we inject fuel from here, and flame stabilizers or V gutters are provided here, and the V gutters provide stabilization they always provide a region of low circulation low speed fluid which always keeps kernel of a flame on.

So that the flame can go on continuously and the combustion takes place in this portion of the after burner, this is the duct where the heat released takes place and stagnation temperature is increased. So when the stagnation temperature is increased and the air then comes out through the converging nozzle we get higher thrust for short duration of time. Notice that the tail end of the nozzle itself is very specialized.

Because when the after burner is not operating then the area of cross sectional area of the nozzle is smaller, and when the after burner is operating the cross-sectional area should become larger, this was something that we saw when we a discussed Rayleigh, and you can see this segment so the nozzle is actually made up of many segments it is not a single piece, it is made up of many of these segments and it is attached to sleeve which moves forwards and backwards.

And as it moves forward and backward the segments spread like petals of a flower to wide open or to be closed okay.

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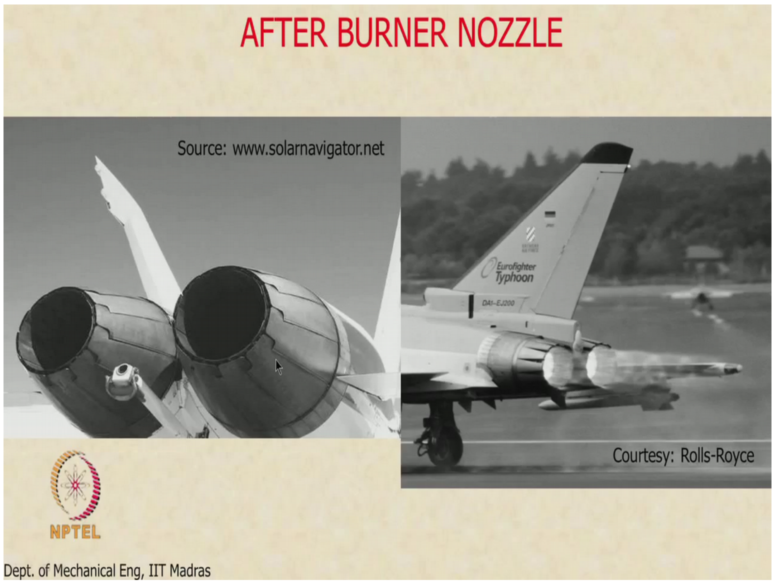

So you can see that here, so you see the segments in the nozzle and it is in the closed position you can see that they are all closed together, and when the after burner is in operation you can see that petals are spread apart like this and you can see the gaps in between the segments and this increases the cross-sectional area of the nozzle, because as you know when the T0 increases the area has to increase to pass the same amount of mass flow rate.

And here we can see the after burner in operation with the nozzle cross-sectional area being more than what it was before, because the nozzle is complicated enough as it is normally the aircraft that uses which are usually military aircraft do not actually have thrust reverses for this. Normally, this aircraft are braked by means of parachutes, so you deploy parachutes which is called para braking, and the parachutes provide the braking when this aircraft land.

Or if they are land on aircraft carrier, then you brake them using arrest cables, so there is a lever that comes out of the bottom of the aircraft which catches the arrest wire on the deck and then brings it to a halt, so they will not do thrust reverser but they can have used for both without afterburner operation and with afterburner operation. So the nozzle becomes more complicated mechanically.

But the advantage as we discussed earlier is the after burner can give good amount of thrust augmentation for short periods of time without increasing the engine size unduly, so the increase in complexity is considerable but increase in weight is not considerable, so this is actually a good choice for thrust augmentation for short periods of time okay. Now that brings us to a close on our discussion of the basic turbojet engine.

So we saw the different components of turbojet engine and the design features and then other considerations for the different components operational details, off design operation, what are the designs in off design operation, we saw all those details for basic turbojet engine. And now what we are going to do is take a look at turbofan engine which is what is widely used in commercial aviation today. So what we will try to do is we will try to see the need for turbofan engine.

Where does that turbofan engine fit in? Why do we need another one? We discussed propellers versus jet and we saw that there were some deficiencies of a propeller which were addressed by a turbojet. Now we try to see we also saw some of the deficiencies of a turbojet and then we will try to see where turbofan fits in this scenario okay.

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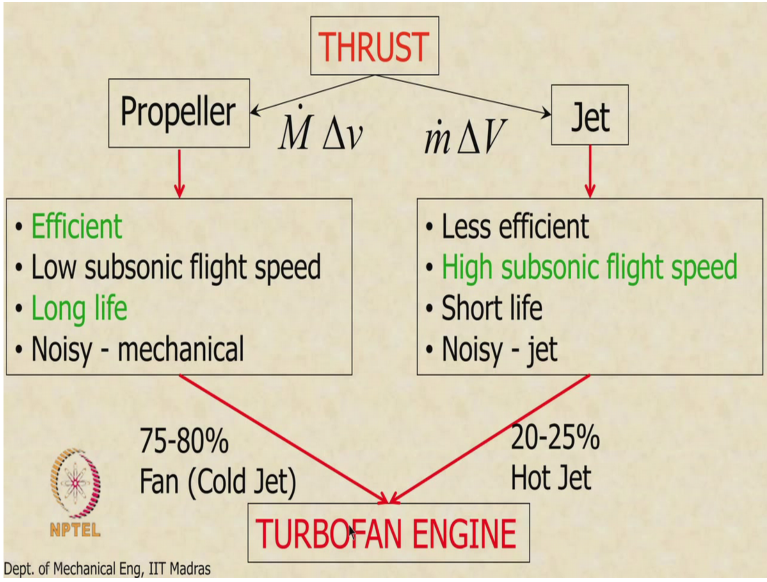

So let us go through a quick recap of what we discussed earlier with regard to propulsion technologies, and if you remember we said that you know the proposition device must generate thrust, and we said that there are 2 ways of doing it. One is to use the propeller which as we said earlier accelerates a large amount of mass through a small change in velocity right. And the advantage is that we listed for the propeller, advantages are listed in green, the disadvantages are in black.

So we saw that efficiency of the propeller can be very high, propulsive efficiency can be very high, it also has a long life mainly because it does not deal with hot air the propeller itself is not exposed to high temperature or high pressure that is a big advantage, so consequently it has a much longer life, but it is very noisy mechanically, that was what we had listed earlier. And the other alternative as we saw was jet propulsion which accelerates as a smaller mass of air through a change in velocity.

But the large change in velocity as we discussed was accomplished through 2 things, firstly we wanted to increase the specific enthalpy. And we increase the specific enthalpy by doing 2 things only is to increase the pressure, the other is to increase the temperature, which means that the components are exposed to high temperature and high pressure and also high RPM which means the life is going to be short and efficiency is also not very high or not as high as propeller for the same flight speed okay.

So if you take a low subsonic flight speed which is the limitation of propeller, let us say that you have a propeller which has maximum efficiency at low subsonic flight speed, if you try to fly a turbojet at the same flight speed efficiency will be less, but the advantage of a jet is that it allows you to cruise at high subsonic flight speeds, where its efficiency is almost comparable to a propeller and actually it is better than that of a propeller when compared to a propeller it is better.

But the life is short because of the exposure to high pressure, high temperature and cyclical loading, and it is also noisy not from the mechanical prospective but from an aerodynamic perspective, the mixing or the high speed exhaust with the ambient causes a lot of aerodynamic noise. So now we can see that this addresses some of the disadvantages of this but not all, so the turbofan hopefully we will address the disadvantages of both these plus keep the retain the advantages of both these right.

So that is what we are looking for in a turbofan engine it is actually I will not say it is a hybrid, it is a combination of both the ideas, the both ideas being if I generate most of my thrust in fashion using by imparting a small velocity change to a large mass of air cold air that seems to be very good from my efficiency and life perspective, but at the same time I want to make sure that I can attain high subsonic flight speeds.

So the idea is why not produce bulk of the thrust using this type of an idea and produce the rest of the thrust using this type of an idea, while retaining this advantage right that is what a turbofan does. So the turbo fan engine generates about 75 to 80% of the thrust using a fan, which uses only a cool air okay, so the fan is not exposed to high pressures or high temperatures and the fan producers about 75 to 80% of the thrust.

The fan is not quite the same as a propeller, there are differences between the 2, and you will highlight those differences but the idea is essentially the same, idea of being imparting a small velocity change to a large mass of air, so the fan does that. And the remainder of the thrust about

20 to 25% comes from the comes from high speed jet, which handles actually hot air, so the hot jet generates about 20 to 25% of thrust that is the idea behind the turbofan engine.

We get to replace all the advantages of the propeller and the efficiency of the jet, meaning this is very efficient and it has a longer life and it also allows high subsonic flight Mach numbers cruise Mach numbers okay.

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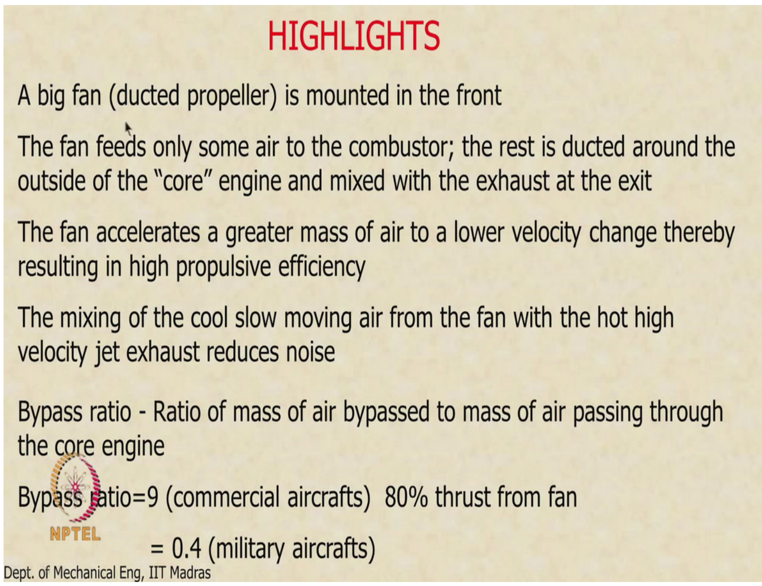

So let us quickly look at the highlights of the turbofan engine, so the most significant noteworthy feature of a turbofan engine is a big fan, some call it a ducted propeller but that is probably not correct but in some sense it is correct in some sense it is not correct okay. It is probably similar to a propeller but not same as propeller. A big fan is mounted in the front of the engine and what happens is the fan because it is so big it captures the air.

The air comes into the fan and much of the air that comes into the fan goes through the fan, only a small amount goes through the core turbojet engine, so the core is the turbojet engine there is a big fan in the front, so only the part of air that goes into the fan goes through the core turbojet engine the reminder goes around the turbojet engine, okay. So the rest of the air is bypass around the turbojet engine only a small portion goes through.

So as you can see from here only some amount or some fraction of the total captured air goes through the combustor, the rest goes to the fan okay. And as we said the fan accelerates a greater mass of air through a lower velocity change, and thereby it has a very high propulsive efficiency okay. Now the noise problem is also address to a large extent in a turbofan the mixing of the cool air from the fan which goes around the core engine mixes around with the high speed hot air from the hot exhaust or the core engine exhaust.

And that reduces the aerodynamic noise to some level to a large extent okay, still a turbofan engine is also noisy, but less noisy much less noisy than a turbojet engine okay. So remember when you went from propeller to turbojet we traded mechanical noise to aerodynamics noise, but now in going from turbojet to turbofan we have reduced the aerodynamic noise also because the slower fan stream mixes with the hot high speed exhaust that comes out of the core engine and the mixing process reduces the average velocity.

Because aerodynamic noise is dependent upon the velocity difference between jet and the surrounding air, since the average velocity goes down the noise also goes down, okay. Now bypass ratio is a concept that is a metric that is used to describe a turbofan engine, bypass ratio is the ratio of air that is bypassed around the engine core engine to the air that goes through the core engine.

In other words, if the engine capture let us a 11 kg per second of air and the bypass ratio is 10 then that means 1 kg per second goes through the core engine, and 10 kg per second goes through the outer engine fan nozzle okay, so 10 to 1 for every 11 kg 10 is ducted outside the core engine, 1 kg per second goes through the core engine. Typical commercial aircrafts today will have bypass ratio as high as 9.

So this would be 9 would be classified as a high bypass ratio turbofan engine, bypass ratio is around 3 to 4 or 5 are usually classified as low bypass ratio or moderate bypass ratio engines low bypass would be <1. For example, military aircraft sometimes have bypass ratio <1 that is low, 3, 4 or 5 is about moderate bypass ratio, and 9 is high bypass ratio. 12, 13, 14 will be ultra-high bypass ratio engines. So these kinds of bypass ratio engines generally produced about 80% of the thrust from the fan okay.

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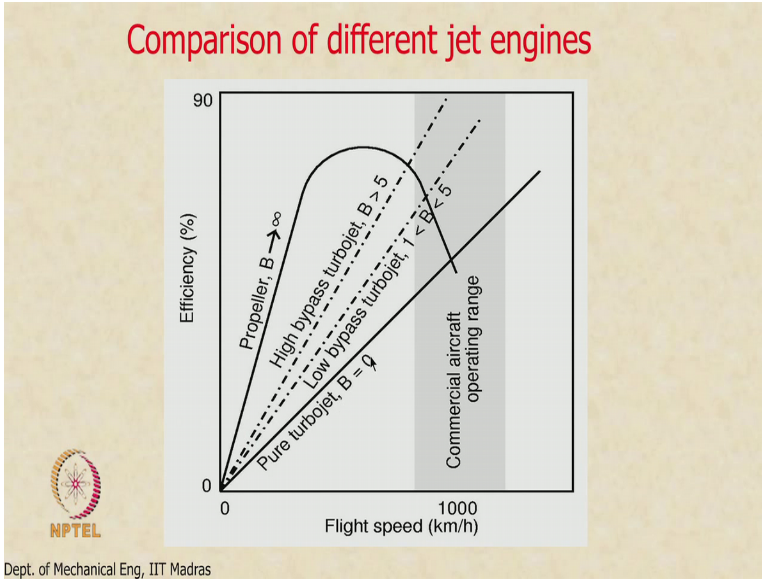

Let us take a look at some more concepts and then see why bypass ratio engine or bypass turbofan engine makes sense okay. So here I have plotted propulsive efficiency versus flight speed, remember we said that we wanted the flight speeds to be in the high subsonic Mach number range, so that means we are typically talking about flight Mach number of about 1000 km per hour or so, and altitude of about 35000 feet, 35 to 40000 feet no more than that okay.

So you can see from here based on the definition of the bypass ratio that we just gave, you can easily see that a turbojet engine will have a bypass ratio of 0 nothing is send around the engine all the air that is captured goes through the core engine, so that has a bypass ratio 0. So you can see the variation of the propulsive efficiency for the pure turbojet engine. On the other hand, a propeller you can think of the propeller as having a bypass ratio of infinity.

Because all the air that is captured is sent around and not that there is no core engine, so that means the bypass ratio itself is actually infinity, so this is the propeller. So these are the 2 extremes in terms of bypass ratios. So you can see that the propulsive efficiency of the propeller increases attains a peak around flight Mach numbers probably around 0.5 or so. 0.5, 0.6 okay.

And then as we said earlier that tip speed becomes higher than the speed of sound, so we have stocks and losses.

So then it begins to fall, so you can see that if you compare the efficiency of a turbojet with that of a propeller at low flight Mach numbers, then you can see the propeller winds hands down, but if you go to high flight high subsonic Mach number flight speed then you can see that the propeller efficiency falls and the turbojet catches up and then exceeds at these kinds of speeds, and this was the reason why we migrated from propeller to turbojet.

But the efficiency is still not as high as what the propeller can provide, and that was what we are talking about we wanted to retain all the advantages of a propeller and all the advantages of the turbojet, their one of the biggest advantage of the propeller is the efficiency, because this efficiency directly translates to fuel economy this is still low compared to this. So what we want are these kinds of efficiencies and these kinds of speeds, which is precisely what bypass engine provides okay.

So you can see that low bypass engines, where the bypass ratio is <5 but generally >1 you can see is about the efficiencies at this flight speeds are comparable to that of the peak efficiency of the propeller okay. In fact, if you go high bypass, you can see that for these flights speeds the efficiency is even greater than the peak efficiency of a propeller. In fact, if you move into the ultra-high bypass ratio the efficiencies will be even higher than this.

And as you can imagine that is where the industry is headed today, ultra-high bypass ratio turbofan engines bypass ratios more than 10, 12 and so on, okay. So the engines that we are going to talk about today will all be in the low to probably high bypass ratio. So you can clearly see the reason why it makes sense to migrate to a turbofan engine from a turbojet engine, the efficiency is better aerodynamic noise is reduced and engine life is also longer.

Because 80% of the thrust is produced by the fan which is not exposed to high pressure or high temperature okay, so it makes sense in every aspect to migrate to turbofan engine technology which is what happened probably in the 80s or so, from the 80s onwards you know we started migrating towards turbofan engines, but the migration was not without the challenges many times you know there are technologies it sounds very promising on paper, but which are impossible to realize.

The turbofan almost proved to be such a technology okay, these are all theoretical calculations right theoretical calculation indicate that the efficiencies can be very high can we realized them in practice is the challenge that engineer faced when they migrated to this technology. Let us look at the engines and then we look at the challenges.

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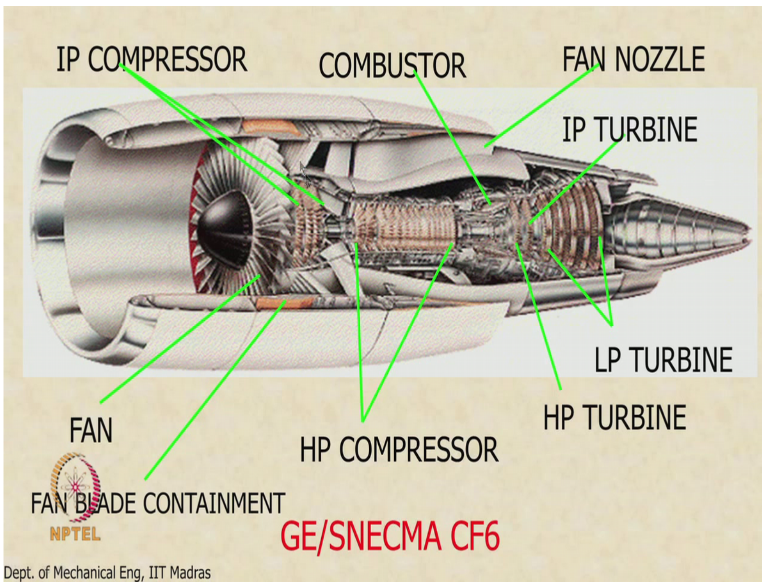

So here we are looking at mid-size engine from GE, this is a CF6 engine typically used in Airbus A 320 Boeing 737 and so on mid-sized aircraft, this is not the largest engine that GE makes we will look at that next. So you can see the general features of the engine there is a big fan in front as you can see, there is an intermediate pressure compressor and there is a high pressure compressor, so you can see the fan blades and the area decreasing here.

And then you see the combustor here, high pressure turbine single stage high pressure turbine drives the 7 or 8 stages of high pressure compressor that is because the blade loading coefficient of a turbine stage can be much, much higher than a compressor. So single high pressure turbine can drive stage can drive seven or eight stages of high pressure compressor. So similarly, you see single one stage of an IP turbine.

And then you see multiple stages of the low pressure turbine, and then you see the nozzle for the hot gas, so this is called the core stream, so the air is captured here and some part of the air goes through this core engine, this is called the core engine and this nozzle is called the core engine nozzle. So the core engine handles high pressure, high temperature air okay, so the nozzle also handles reasonably high pressure reasonably high temperature, so this is called the hot exhaust or hot nozzle.

In contrast, the rest of the air goes to the fan, these are the rotating fan blades, you see a set of stationary fan blades and then you see the fan nozzle, this is why a fan is different from a propeller. Remember we looked at propeller sometime back and the propeller does not have a nozzle, the propeller directly imparts a velocity change to the fluid, and that is directly transmitted as thrust.

Whereas a fan causes the pressure of the air to increase not by a large amount by a small amount, and then because the mass flow rate of air is very large that small pressure difference there increase in enthalpy is converted to kinetic energy in the fan nozzle. So that is why a fan is different from a propeller, a fan uses a nozzle to produce thrust, whereas a propeller generates thrust directly okay.

So the fan nozzle is also called the cold nozzle because they are coming out of here as cold, and this is called hot nozzle okay. And in this engine you also see the fan blade containment here, the fan blade containment is very important safety feature and we will talk more about this later on, so you can see that this is a band that is placed in the nacelle around the fan blades, so you see this band here which is around the fan blades in the engine nacelle.

And the purpose of this is to contain any fan blade which might become dislodged due to some catastrophic event, let us say a bird hit or some other problem if a fan blade comes lose this blades actually can be they are actually quite big in size, so if it comes through it can cause a lot of damage to the engine, and to the fuselage, the cabin compartment, passengers and so on. So this is a safety feature that is a must for all turbofan engine okay fan blade containment.

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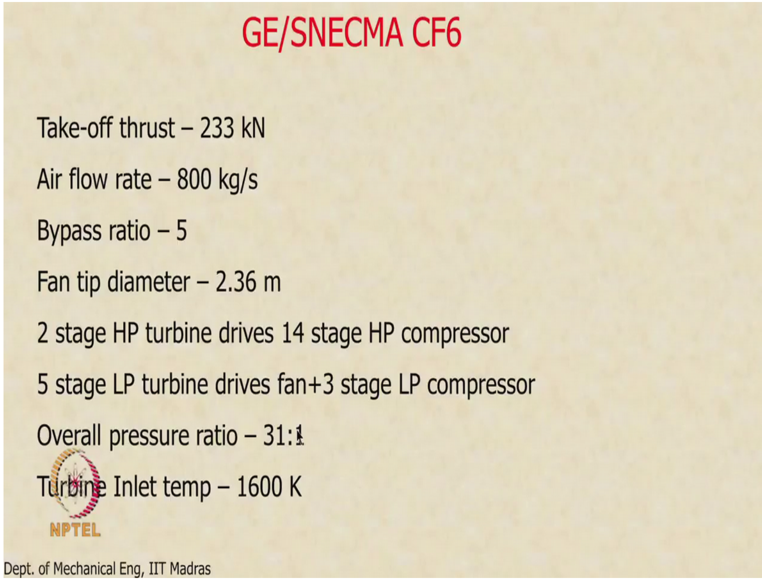

So some of the specs of this engine we can see that it is a low bypass ratio engine bypass ratio of 5, handles about 800 kg per second at take-off, fan tip diameter as you can see how big it is? It is about 2.36 meters, so you can imagine the fan blades are quite big right. So we have 2 stage HP turbine which drives 14 stage HP compressor, 5 stage low pressure turbine drives fan +3 stage low pressure compressor.

Overall pressure ratio about 31 to 1, remember this is a medium size engine, so it is about 31 to 1. Turbine inlet temperature about 1600 Kelvin.

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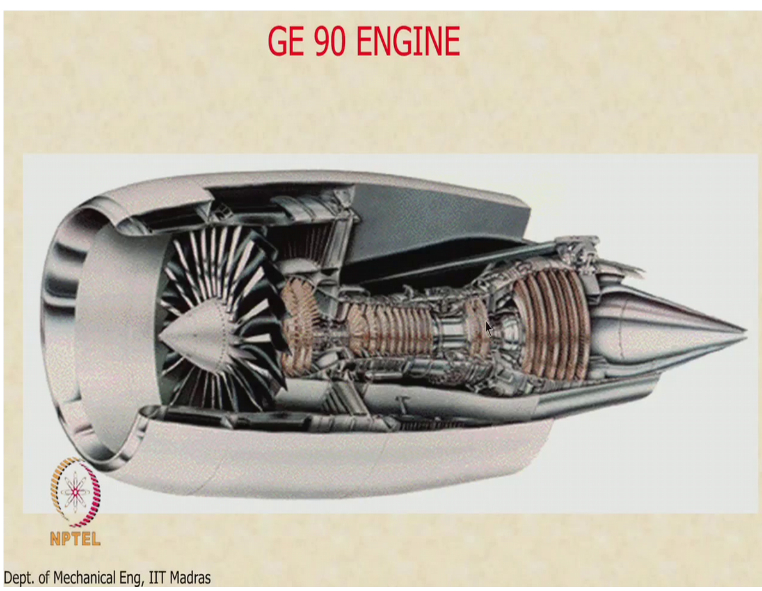

The next engine that we will talk about is the GE90 engine, which is probably the biggest engine that GE offers next only to the Gen X engine which is the latest offering. This is probably the largest engine in service today the biggest engine in terms of thrust produced, biggest engine in service. You again see the same kind of thing the fan, the moving blades of the fan, the stator blades of the fan and the fan nozzle.

Then again you see the core engine, compressor blades, the combustor, the turbine blades and the low pressure turbine blades and the hot nozzle okay, so this is a big engine.

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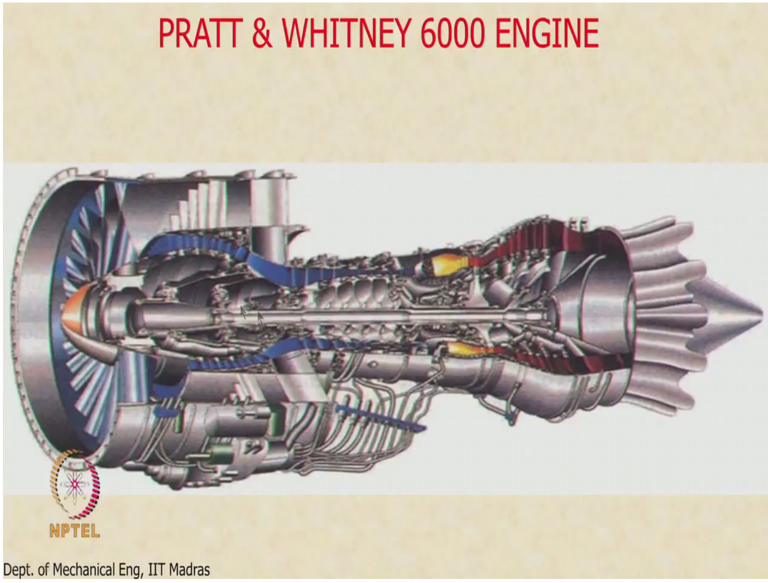

And this offering from Pratt and Whitney is also comparable in terms of thrust rating and so on. So once again you see the core engine, the compressor blades, different stage of the compressor, combustor, turbine stages and then the nozzle here okay. The nozzle has these kinds of corrugations to enhance mixing and reduce the noise okay, so these corrugations generate vortices, which enhances mixing in this direction and reduces the aerodynamic noise that the engine produces, you also see the fan blade, the stator vanes and the fan passage and also the fan nozzle.

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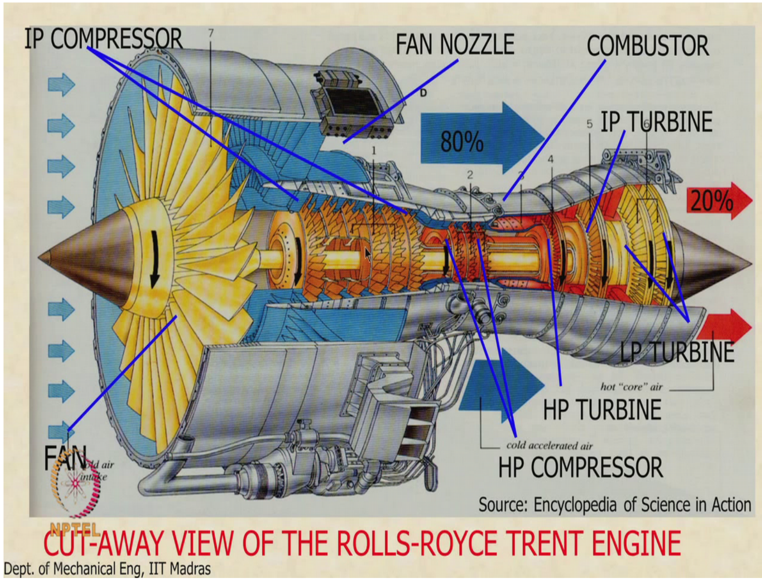

A comparable size engine here is an offering from Rolls-Royce, the similar rating you see the big fan in different. Rolls-Royce typically tends to use 3 shafts okay we will see why in a minute, so this is the fan, then there is an intermediate pressure compressor as you can see, and then there is a high pressure compressor, high pressure turbine, intermediate pressure turbine and low pressure turbine.

And you can see that the air that goes through the fan rotating fan blades, stationery guide vanes in the fan passage, this is the fan nozzle okay. Similarly, here you get the hot exhaust which comes out through here the nozzle will fit here okay, and these stream producers about 20% of the thrust as I said before approximately varies from engine to engine. And this stream the cold stream producers about 80% of the thrust okay.

Notice the in the case of multiple shafts notice one shaft within the other, you can see the innermost shaft which drive the fan blade, and the next shaft which drives the intermediate pressure compressor, and the even bigger shaft which drives the high pressure compressors. So all these three shafts are placed one inside the other and they all rotate like this at different RPMs okay, so they are all concentric shafts running one inside the other.

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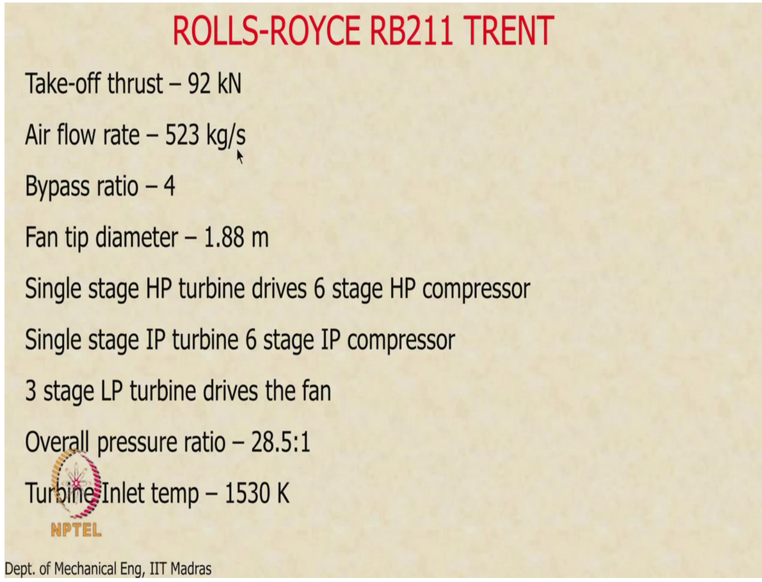

And typically specs for the engine is about 90 to 100 kilonewtons of thrust, air flow rate about 5:23 kilogram per second, again these engines come in different specifications okay, same basic architecture but at different thrust ratings and so on. This one that the bypass ratio again ranges from 4 to 10 in this particular architecture, fan tip diameter for all these engines are about 2 meters or so, and pressure ratio for a mid-size engine will be about 30 or so to 1.

Inlet temperature again these are what we think they are in a 1530 is probably on the lower side for this engine, but as the rating goes up the turbine inlet temperature also will go up depending upon the engine right. So we have looked at the general architecture of the turbofan engine, and let me summarize the advantages and disadvantages of a bypass engine okay.

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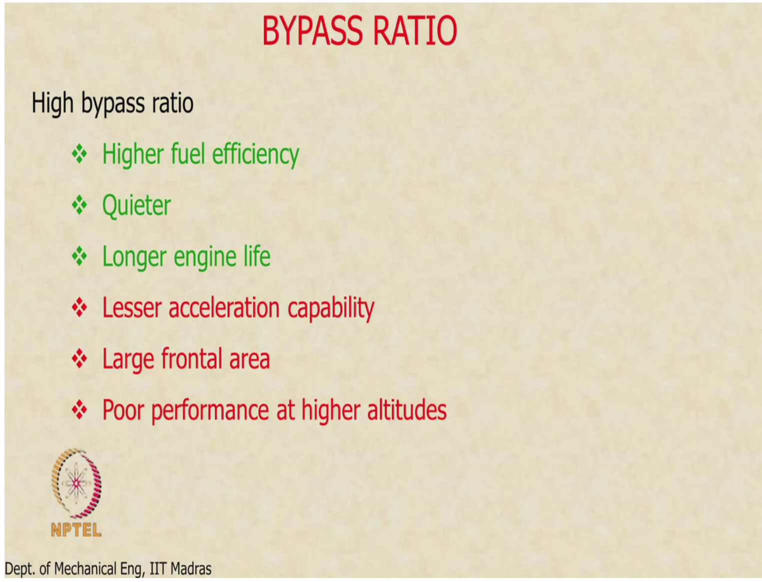

So not all actually is good for the bypass engines okay, so if you look at the high bypass ratio turbofan engines definitely higher fuel efficiency because the propulsive efficiency is better. And the engines are also quieter because as I said the cold air mixes with the high speed hot air thereby reducing the velocity gradient, when the stream comes out of the engine and mixes with the ambient, so the aerodynamic noises has brought down.

Longer engine life certainly, because 80% of the thrust is produced by components which are not exposed to high pressure or high temperature okay. But because the size of the engine is bigger definitely mechanical inertia plays a role, so the acceleration of turbofan engine is less compared to a turbojet engine okay. And the increased frontal area remember now the bypass ratio is 5 or 6 or 10 that means your propeller is going to be like this to capture that much amount of air.

So as the bypass ratio increases the fan diameter also increases the frontal area increases, which means that drag due to the nacelle also increases, so the nacelle drag increases with increasing frontal area. And at higher altitudes there is generally a degradation in the performance of the turbofan engines, although for commercial aviation this not a major problem, what this means is that you cannot fly this in other types of aircraft.

The higher bypass ratio engines cannot be flown or flying at let us a 50 or 60000 feet altitude, they cannot go much beyond 35 to 40000 feet altitude okay.

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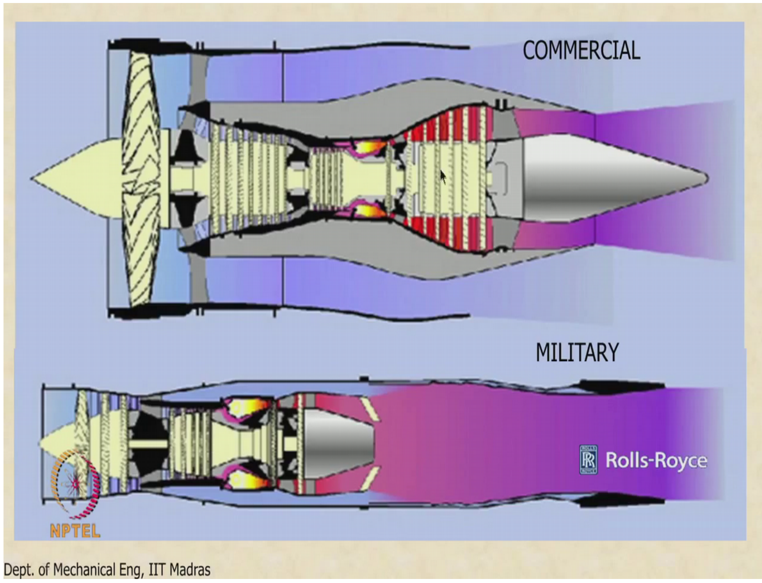

So here is a pictorial view of a high bypass ratio engine and low bypass ratio engine, the low bypass ratio engines are typically employed for military applications, and the high bypass ratio engines are typically employed for commercial aviation applications okay. You can see the increase in diameter with increasing bypass ratio, and the consequent increase in the frontal drag okay.

Ultra high bypass ratio engines will have larger areas, and as we will see later on, this would mean that you may not be able to mount an ultra-high bypass ratio engine an existing aircraft wings because the wings maybe too close to the ground for ultra-high bypass ratio engine. So you have to think about now the technological challenges where do you mount such engines?

We mount them above the wing or on the fuselage, where should they be mounted, the weight is also quite high. So where the engine is mounted is also very important, so that will have other technological challenges.

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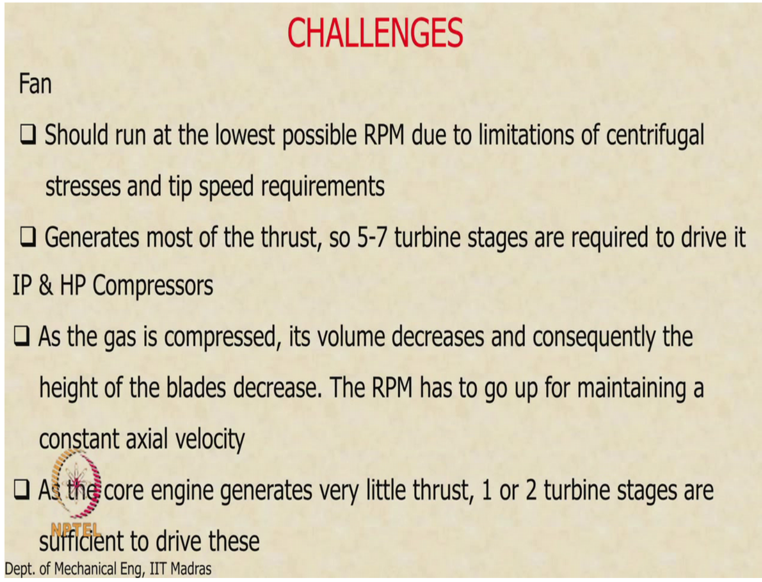

Now what we are going to see next is, at least on paper based on whatever I have shown you it makes perfect sense to migrate to a turbofan technology from a turbojet technology, but what are the technological challenges that we will face when we decide to make such a transition, and that is what we are going to talk about, and how do we overcome these challenges okay, and of course you know it is quite reasonable that the challenge comes from the fan from one component the fan that is understandable.

Because that is only new thing that we have done right, so the bypass means a fan right. Other components you already know the challenges and we have already dealt with them, we saw that the high pressure turbine blade is exposed to high temperatures, high pressures and high RPM. So we decided that the blade would be cooled, blades would be fabricated using single crystals, then we will provide a thermal barrier coating, so we overcame all the challenges right.

And now we are adding a new component the fan understandably the fan poses the biggest technological challenge here. What are the challenges? Number 1 for a bypass ratio let us say of 5 above 5 okay, the diameters become quite high, so when the diameters become quite high when the fans spins the centrifugal loads towards the tip of the blade is going to be quite high it will be quiet high.

So from that perspective what we would like to have is that the fan should run at the lowest possible RPM because of centrifugal stress that is one issue, the second issue is the same challenge that we had earlier with propellers. Remember as the tip speed increases, the tip speed may exceed the speed of the sound, then there will be shocks and losses okay, so that is constraint that we already face and so that is again going to be a constraint okay.

So these are 2 major things centrifugal stress and tip speed requirements, but at the same time we cannot run the fan at an arbitrarily low speed because the turbine must run at the same speed to run the fan, so the lowest speed that we can get is ultimately going to be determined by the lowest speed at which we can run the low pressure stages of the turbine, we may not be able to run them at let us say 1000 RPM.

They may have to be at a reasonable speed for the axial velocity to remain constant, otherwise we will not be able to get the axial velocity or the flow to go through this blade passages, they need to spin at a reasonably high speed, so that is what this is going to restrict the RPM for the fan okay. Now as he said earlier this generates about 75 to 80% of the thrust, so a large number of turbine stages are required to drive it.

Which means that if I reduce the speed of the turbine too much, then I will not be able to get the flow to go through all the stages of the turbine, so that is the constraint that I must deal with. Now the other thing is that the intermediate and especially the high pressure compressor as we mentioned earlier as the gas is compressed the density increases right that means for the axial velocity to remain the same my cross-sectional area should go down that means the blade height goes down.

But as the blade height goes down I must make sure that the air can pass through, and the only way I can do that is to spin them at high speed, so the high pressure compressor must spin at considerably higher speed than the IP compressor or the fan to maintain a constant axial velocity okay that is a constraint that we have. So but fortunately as the core engine generator only 25% of the thrust 1 or 2 turbine stages are sufficient to drive these compressors intermediate and high pressure compressor.

Whereas this one will require a lot of turbine stages to drive it okay. A typical number kind of number that we are talking about for a fan power rating for a fan is that approximately for this type of engines the bigger engines that I am talking about the power that the turbine provides to the fan is of the order of about 30000 HP or so, it is quite a large amount of power okay.

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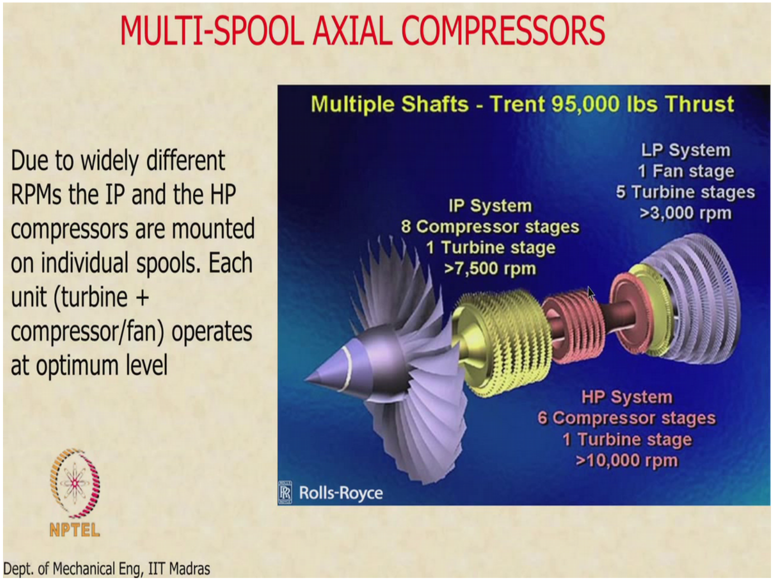

So because we have widely different requirements for RPM right, the only way we can actually meet this challenge we want the fan to run at low speed at the same time the other components have to run at a higher RPM, so only way we can accommodate such widely differing RPM used to have the Multi-Spool technology. So there were the first technological challenges that had to be overcome, and it was overcome by using a revolutionary technology called the multi-spool technology.

Shafts within each other and spinning at different RPMs, and we can see the wide range of RPMs from this graphic, we can see the that the high pressure turbine system runs at speeds about 10000 RPM or more, because it has the shortest blades, so this runs at speeds very highly RPMs. The intermediate pressure which is in yellow here runs at RPMs around 3000 or so okay, I am sorry it runs at 7500 RPMs or so, the intermediate pressure runs at 7500 and the fan as you can see runs at about 3000 RPM or so.

And that is the lowest possible RPM that we can do when it is connected directly to the turbine, so the speeds are optimized, so that each unit that is a turbine plus a compressor unit both operate at optimum levels okay. So we decided upon the aerodynamics of the compressor and the turbine blades and the fan blades, so that when we coupled them this way the RPM is such that all of them operate at the best possible aerodynamic efficiency.

But this is a very complex piece of technology, especially from a lubrication point of view having these kinds of shafts inside one inside the other spinning at different speeds poses tremendous challenge from a lubrication perspective okay. And remember the shafts are also hollow right that means the weight of the blades has to be borne by this hollow shaft which is an extremely challenging task.

Previously, the shafts were a solid shaft, now the shafts are hollow, so that poses a tremendous amount of challenge okay. The only advantage is that the fan sits on the innermost shaft right, the HP set is the outermost one, the IP set is the inner one, the fan is the innermost one, fortunately the fan also is the heaviest, but fortunately the fans sits on solid shaft, because the innermost one is a solid shaft right.

But it is still a challenge to manufacture this multiple shafts or multi-spool shafts and make them reliable during operation that is a very challenging task which has been overcome by all the engine manufacturers in each and different ways. So we accommodated the first requirement which is that the fan should run at as slow an RPM as possible, so we have now come to a stage where we say that 3000 RPM is about the smallest that the fan can run at, so that is the first thing that we have done.

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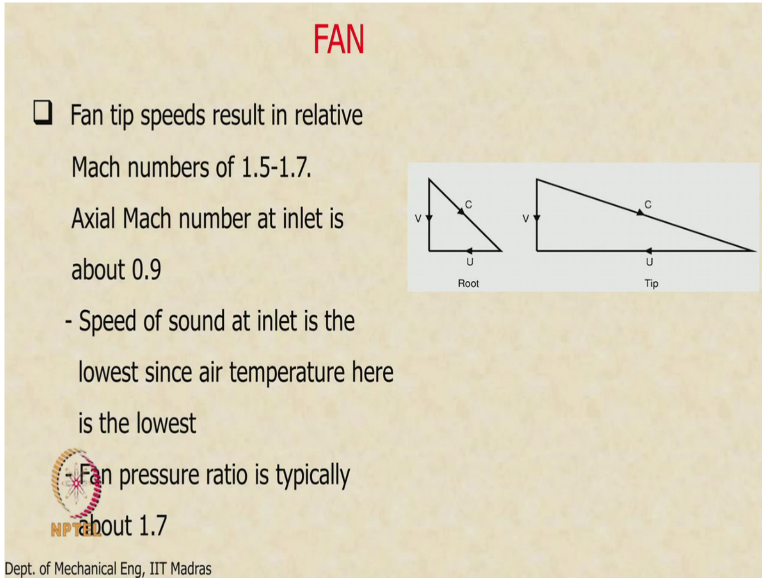

And we have supported the difference in speeds with multiple spool technology okay, but the challenge is do not stop there, let us say that this spin the fan spins at 3000 RPM, now unfortunately because of the bypass ratio that are required remember the diameter is determined by the bypass ratio, now we know the speed so which means I can determine the tip speed as you know that fan tip diameter is about 2 meters or so knowing the RPM I can determine the tip speed.

And what happens is 2 things actually makes 1 or 2 issues makes this very difficult, unfortunately the fan handles the coldest air, the air that is coming into the engine that is at the lowest temperature across the entire engine which means that the speed of sound is also the lowest possible okay that is one of the challenges. The other challenge of course is the RPM and the diameter, so what happens is because of this and the RPM you have the flow that approaches the fan becomes subsonic at the root section and supersonic at the tip section.

Remember you must bear this in mind this fact in mind I am saying the relative velocity Mach number based on relative velocity approaching the fan becomes supersonic, the aircraft is still cruising at high subsonic flight Mach numbers that is this component V, the absolute velocity component V is still subsonic right, so that is the same at the root and tip because the flight is moving forward at the same speed, there is a root section or tip section that absolute velocity is the same and that is subsonic.

But because the blade speed varies so much from root to tip, remember this is R omega, this is also R omega, because the tip diameter is so much higher than the root diameter this increases, so for the same absolute velocity you can see the relative velocity is very high. So the relative Mach number or the Mach number of the flow approaching the fan blade in a relative co-ordinate is subsonic, whereas at the tip it is supersonic, which means that I have mixed flow now.

The fan now actually now has to be designed to handle transonic flow, and remember this was the challenge that we faced with me propeller, but the propeller is open okay, whereas here the fan is duct, so there are few things that we can do, but this is a challenge that we faced earlier right. So we must design the fan to handle transonic flows okay, and fan pressure ratio remember we said that fan increases the pressure of the large amount of air and then that enthalpy is extracted or converted to kinetic energy in the fan nozzles okay.

So typical pressure ratio in a fan is about 1.7 today, best fan 1.7 to 1.8 or so okay, how do we realize this type of pressure rise in a fan blade? Same is what we did earlier, what did we do earlier in the compressor. This is remembered this is compression through deceleration of the relative component of velocity, so that means the blade passage must have appropriate cross-sectional variation to accomplish pressure rise decelerated the air and accomplish the pressure rise.

What would the blade passage area look like if it is subsonic, it would be diverging passage area just like our compressor, what would it be if it is supersonic that is the reason why we studied converging diverging diffusers, how do we decelerate a supersonic stream and increase pressure rise. So it is not only useful in in supersonic intake, but it is also important in fan design, so this has to be done extremely careful.

Because you know the problems that are associated with decelerating a supersonic stream and recovering the momentum as pressure, but that is essentially what we must do here when the relative Mach number becomes supersonic. So let us see how this is done.

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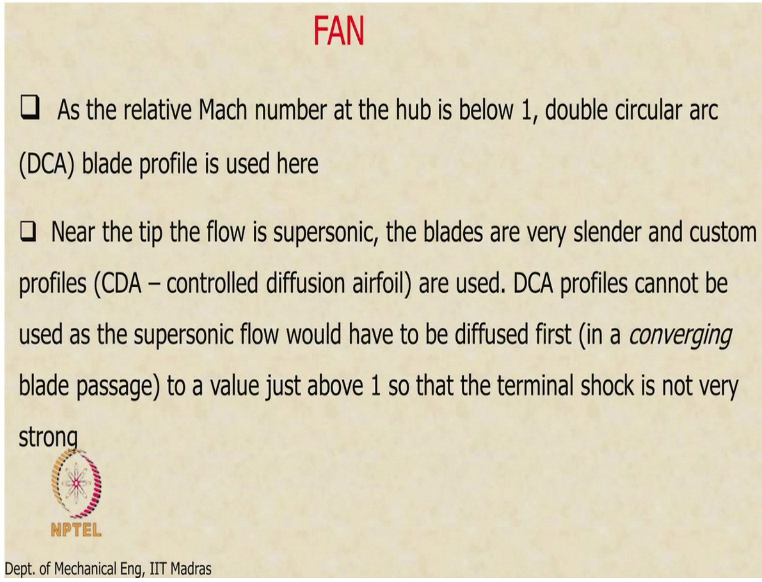

So the relative Mach number at the hub is below 1, so normally the blade section okay the blade section is made up of 2 circular arcs okay, so this is called as double circular arc profile for the subsonic section it is called DCA blade profile.

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