Gas Dynamics and Propulsion
Dr. Babu Viswanathan
Department of Mechanical Engineering
Indian Institute of Technology - Madras

Lecture – 37
Emerging Trends / Ramjets

In the last class, we looked at the frontiers of the future or improvements, directions in which improvements are being sought in the aircraft engine industry and we said that there are 2 major directions in which improvements are being sought.

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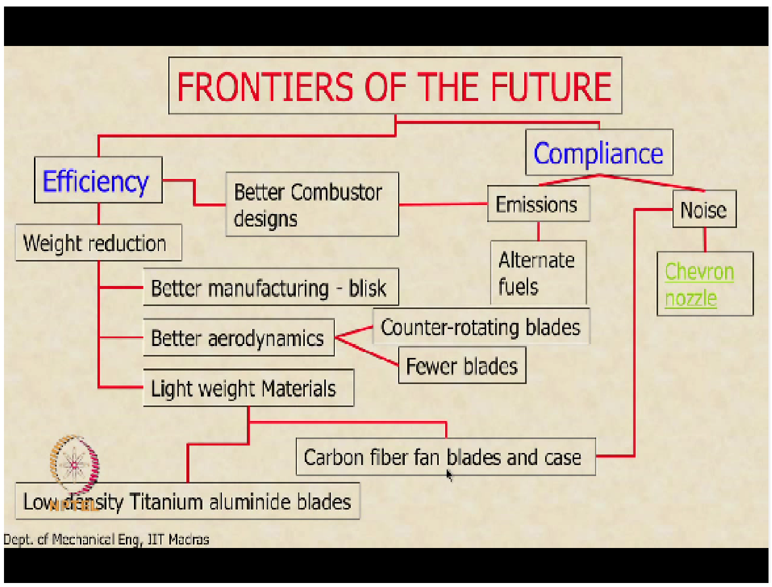

First one is efficiency. First and foremost is always efficiency and here we mention that a better combustor designs and weight reduction are 2 very important directions in which improvements are being sought and weight reduction itself can come from several different means. For example the weight reduction could be a result of better manufacturing and one example of that is the blisk which is new manufacturing technique for manufacturing blades and the disk together which results in savings in weight.

The next one was better aerodynamics of the turbomachinery stages. So this could be due to for example counter-rotating stator blades which will increase the work interaction per stage and thereby reduce the number of stages, that is one possibility. The second possibility is improving the efficiency of each stage itself which will result in fewer blades and consequently weight reduction.

So better aerodynamics always results in weight reduction through one of these 2 avenues and the third one is weight reduction in the literal sense, meaning we use lightweight materials and so here we are talking about materials such as a carbon fibre for a fan blade and the casing and we are also talking about the turbomachinery, the compressor and turbine blades being manufactured using low-density titanium aluminide blades which makes the blades lighter. So even without reducing the number of blades, we can actually reduce the weight.

So all these strategies will result in weight reduction. Better combustor design will definitely result in better efficiency. The other avenue in which improvement is being sought is compliance, better compliance. By compliance we mean emission compliance and also noise compliance. Now emission compliance is being improved again through 1 or 2 avenues. One of course is to use alternate fuels.

So these are synthetic fuels which are designed so that after they undergo combustion, you are not left with so much NOx. So the structure, chemical structure of the fuel itself is such that the amount of NOx produced is less. So this discourages NOx production and there are many chemical companies which are manufacturing these types of synthetic fuels for use in aviation industry today, okay and the other way in which we can reduce emission again is to use better combustor designs.

So as we can see from here, better combustor design will result in better combustion efficiency which will have the effect of reducing the amount of fuel that is being used which will also result in reduction of emissions. So as we keep reducing the amount of fuel that we are using, the emissions will also go down concomitant to that. So better combustor design has benefits in both direction, both in terms of emission as well as in terms of efficiency.

The other compliance thrust that airline companies are following is on noise. Okay. Although the noise, if you remember propellers produce a lot of mechanical noise, turbojets produce a lot of aerodynamic noise. So when we switched to turbofan engine, the aerodynamic noise was reduced because the cold air mixes with the hot air and that diminishes the velocity gradients which causes aerodynamic noise but still now by the standards of 2014, even the turbofan engine actually makes a lot of noise. So the noise has to be further reduced.

So airline companies are trying to reduce noise in many different ways, okay. One way to reduce aerodynamic noise is to use something called a Chevron nozzle. This is a new concept which is being flown in the latest engines.

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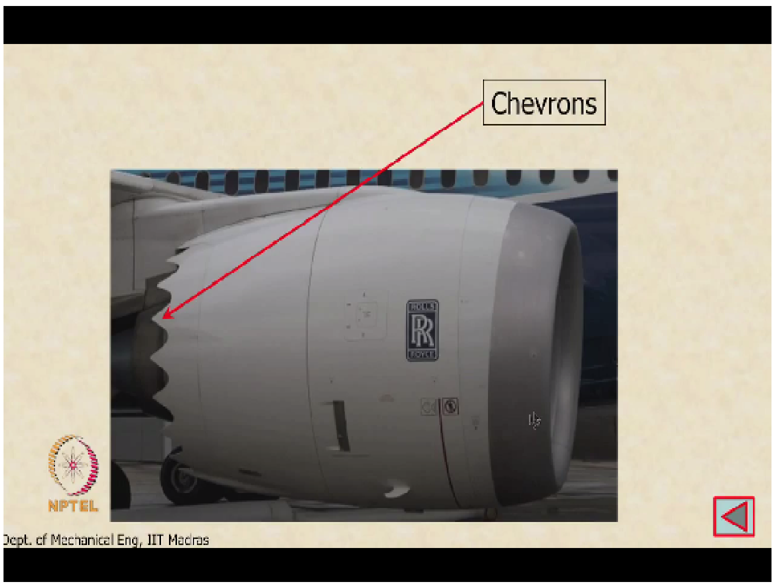

Let us take a quick look at a Chevron nozzle. So here we can see the Chevron nozzle. See this triangular serrations at the trailing edge of the fan nozzle and also the core engine nozzle improve mixing. This triangular pieces increase the generation of streamwise vorticity and the streamwise vorticity creates much better mixing of the air, much better short-term mixing of the air so that over a longer distance, the velocity gradients go down because the high speed air is much better mixed, the overall velocity goes down.

So the noise also goes down. So Chevron is a very promising concept which is already being used in many of the new engines, okay. This is supposed to reduce noise by, aerodynamic noise by as much as 50%. This is very normal concept and the fact that it is a static device, is also good because this does not need any active adjustment. This will reduce the noise irrespective of the operating condition, subject to certain restrictions, okay.

In some cases, it is possible that this may reduce high-frequency noise with an increase in low frequency component of the noise and vice versa. So that is quite possible but by and large, Chevron's design properly will cause a reduction in noise and that is something that is being used in the latest engines today. So this is one of reducing aerodynamic noise. The other noise from turbofan engine is of course structural noise, right, vibrations and structural noise and one way to reduce this structural noise is to use these kinds of fan blades and fan casing.

So if you use a carbon fibre fan blade or case, the noise is damped much more effectively and the structure born noise goes down considerably in this new turbofan engines. So these are the lines of research or frontiers of research which are being pursued in the aircraft industry today in so far as engines are concerned, okay. Any questions? So this discussion brings us to a close on turbofan engines. What we will do next is to look at ramjet's and thrust calculations for ramjet to be followed by scramjets.

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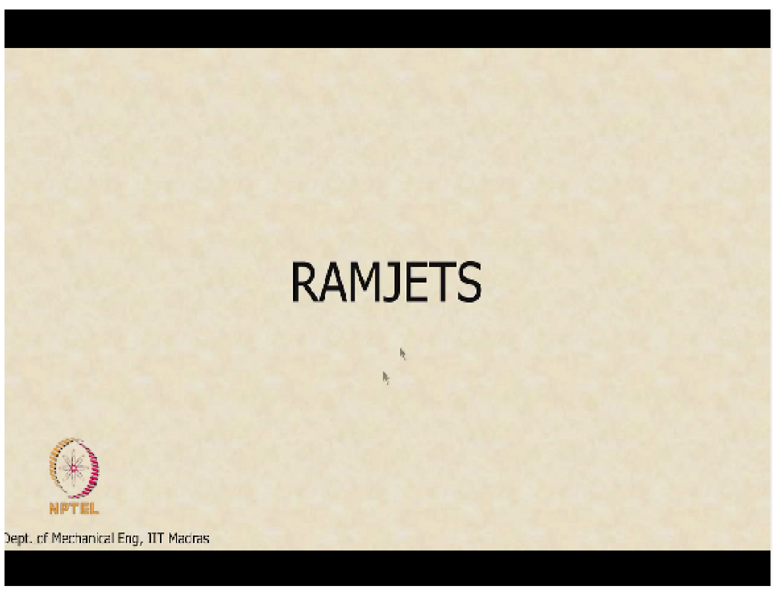

So here we see picture of ramjet engines.

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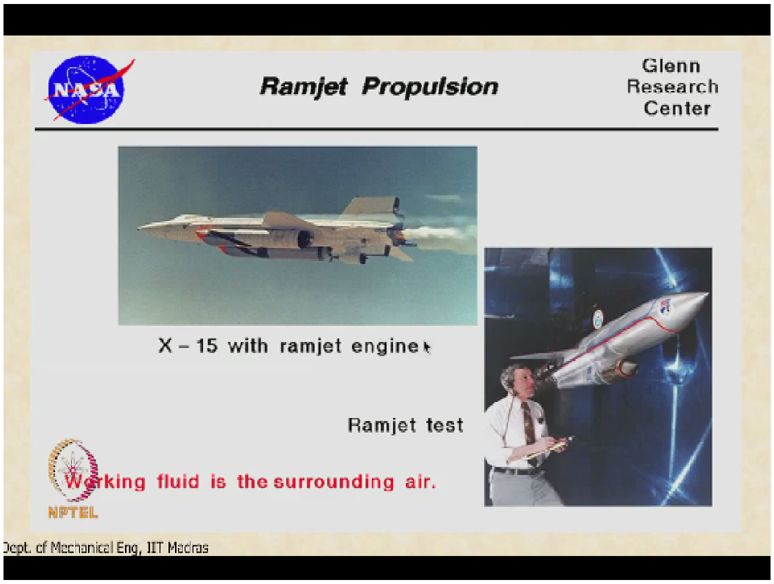

Basically so here is a picture of a ramjet engine. This is X15, this is an experimental aircraft which as we can see in this figure is fitted with a ramjet engine and if you look at this picture of the ramjet, notice that the ramjet engine itself is located here. So this is the vehicle which is propelled by the ramjet engine which sits over here, okay. Now ramjet engines are used when the flight Mach number is sustained supersonic flight Mach number.

So the ramjet engines are used for these types of applications. When the vehicle cruises in a sustained fashion at supersonic Mach numbers, usually less than 3 or so, about less than 3 or may be less than 4 but no more than 4. So when the vehicle cruises at such Mach numbers in a sustained manner, then ramjet engines can be used, okay.

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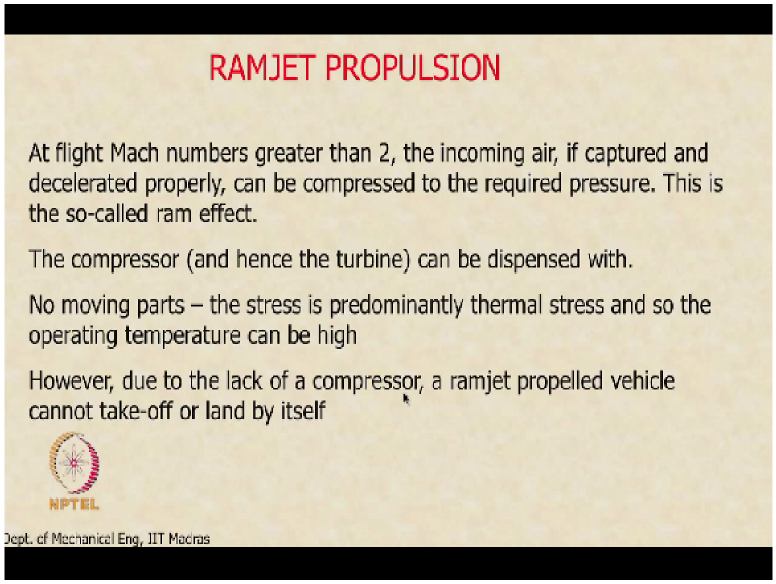

The main idea behind the ramjet engine is described here, at flight Mach numbers greater than 2, the idea is to capture the incoming air properly and decelerate it using a well-designed intake pressure, I mean by using a well-designed supersonic intake. So if you do that then the incoming air can be compressed to the required pressure, okay. So we decelerate the high-speed air and convert the momentum into pressure, okay.

So this is the so-called ram effect, the high-speed stream is decelerated and the momentum is converted to pressure. So this is why the engine is also called a ramjet engine. Now for this thing to work, the intake has to be designed extremely carefully and the intake becomes the critical component in such a device. The advantage is, if you are going to realise all the required pressure using the intake itself, then we do not require a compressor to compress the air and if you do not require a compressor, then you do not require a turbine to run the compressor.

So that can also be dispensed with. So the advantage is that the engine has no moving parts which means that there are no centrifugal stresses, there is no high RPM, there is no corresponding centrifugal stress and so on. The stress is predominantly thermal stress only and consequently, the ramjet engines typically operate at much higher temperatures than turbofan or turbojet engines because the limitation due to centrifugal stress is no longer there.

We can elevate the, increase the operating temperature to higher levels, okay and provided we give sufficient protection, high-temperature production for the components, we can operate at much higher temperatures but the difficulty is, because it does not have a compressor, the intake will start working only when it has supersonic air entering the intake. Only when the air has a high momentum or if the vehicle is already moving at supersonic speed, then we can take the air and decelerate it and compress it, which means that the ramjet propelled vehicle cannot take off or land by itself.

It will need something else to help it, either it must be fitted on to a mother aircraft or it must have engines which can operate both in the turbojet mode and also in the ramjet mode, okay. So we will look at this technology also, the turboramjet engine uses a turbojet for takeoff, landing and low flight-speed operations and it uses a ramjet for sustained flights at supersonic speeds.

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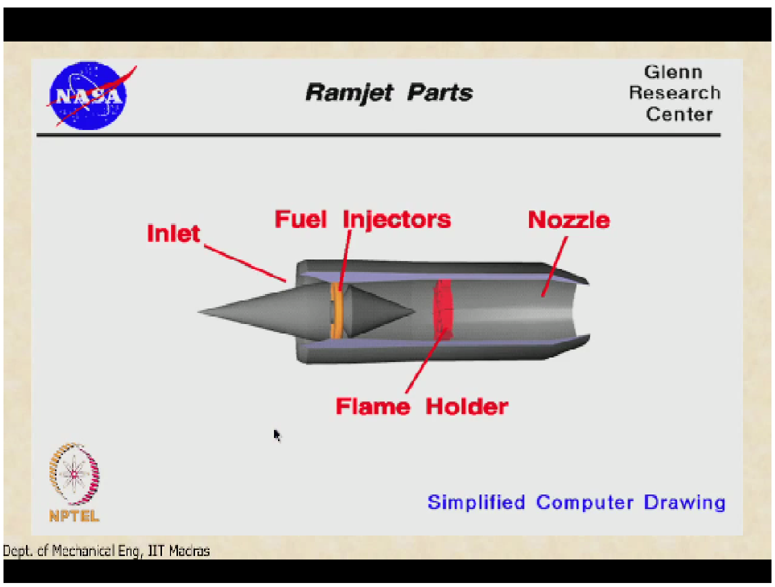

Ramjet engine actually is extremely simple, at least in concept. So conceptually, we can see that the engine has very few parts. There is no compressor, there is no turbine, it has an intake which in this case is shown in the axisymmetric form. So there is an axisymmetric intake. It can also be a 2-dimensional intake, both are used now. So this is as an axisymmetric conflagration. So fuel is injected at the end of the intake.

And because the air usually moves at reasonably high-speeds at the end of the intake, the fuel is injected here and the combustion usually starts in this region, okay. Combustion is initiated in this region and terminates just before it enters the nozzle and we use, depending upon the application, convergent or convergent-diversion nozzle, both are used, okay. So it is extremely simple, the flame holders are required to ensure that we have stable combustion in this kind of high-speed situation.

So as you can see, the combustor does not require any elaborate design. Basically this combustor is just like what we saw in an after-burning engine. The after-burning engine has a duct in which we inject fuel, there is a flame holder, so the combustion take place. So the ramjet combustor is more or less similar to the afterburner combustor, a very simple, it is not a combustor, it is just a duct in which we inject fuel and burn it, for all intents and purposes. So the critical component here is the intake, okay and that is what we will look at as we go along.

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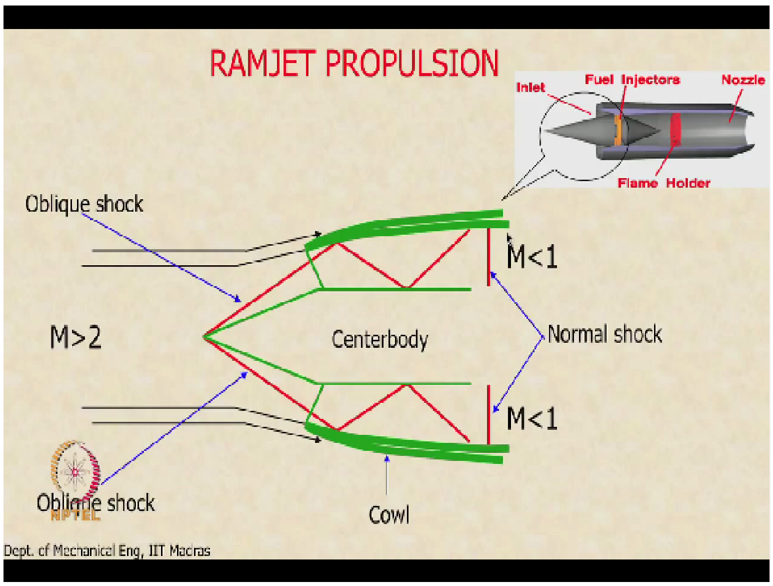

So as we can see in the axisymmetric version of this engine, the intake looks like this. There is a center body and there is a cowl which is outside this. So the supersonic flow comes from left to right here and the centre body initiates an oblique shock which goes like this and the shock is reflected usually and there is a terminal normal shock. So the idea is, decelerate the flow as it goes through these multiple reflections from a Mach number.

Which may be above 2 to a value which is close to 1.5 or 1.6 so that the terminal shock does not incur a lot of loss of stagnation pressure. So we try to bring it down to Mach number 1.7 or so in this situation so the combustor follows from here. Combustion in this case takes place at subsonic flights, I am sorry, subsonic speeds of the fluid, okay. The combustion is still at subsonic speeds.

But compressibility effects will likely be significant in this case because the velocities and the Mach number in contrast to a turbojet compressor, I am sorry, in contrast to a turbojet engine. Now the velocities of the fluid entering the combustor can be reasonably high, subsonic but reasonably high. So compressibility effects can be significant in this case, okay. So the idea is to have multiple oblique shocks to decelerate the flow terminating in a normal shock at Mach numbers around 1.7 or so. This is the axisymmetric version of the ramjet engine.

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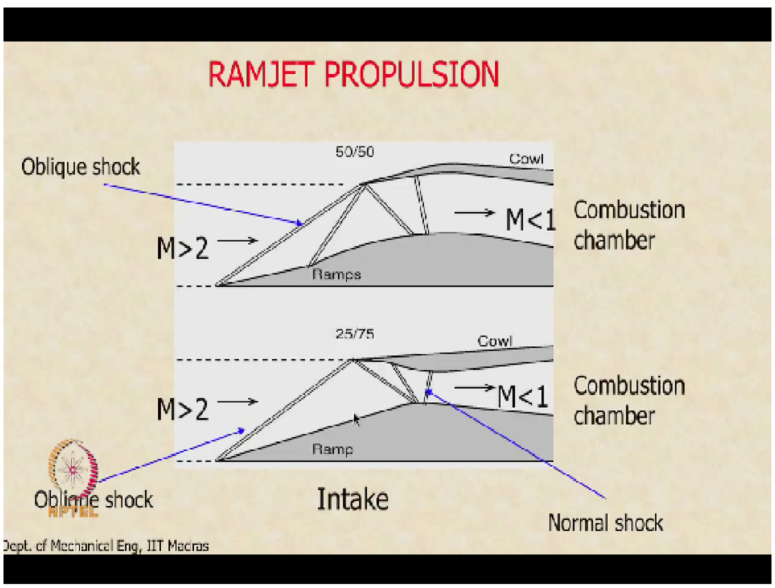

So here I am showing you the ramjet engine with 2-D type of intake, rectangular intake, so the intake is rectangular in cross-section. This is the cross-sectional view. So here you see the same kind of idea. This has multiple ramps and a cowl. So the supersonic flow comes from here, so each corner of the ramp generates an oblique shock and the flow is decelerated here and we can have some more reflections inside here or additional oblique shocks triggered terminating in a weak normal shock.

Weak meaning around Mach numbers 1.5 or 1.6, same concept and then there is usually a passage where the flow can be further decelerated with the subsequent increase in pressure.

Depending on the orientation of the shocks, you can get different kinds of situations. The important thing to see here is that part of the compression takes place externally and part of the compression takes place internally.

So depending upon how we apportion the overall pressure rise, we get different types of designs. So 50-50 here means 50% of the compression takes place outside and 50 inside. 25-75 means one-fourth here and three-fourths inside, okay. We will take a closer look at these types of intakes further down but the intake is the most critical component of the ramjet engine.

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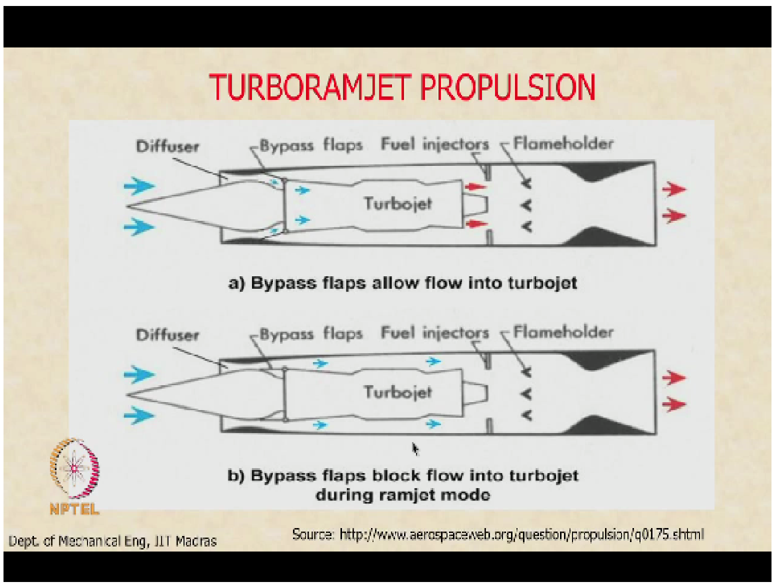

Now as I said the ramjet engine, because it lacks a compressor, it cannot take off or land by itself. So one way to get around this is to use something called a turboramjet engine. Turboramjet engine operates in a turbojet mode as we can see from here. Turbojet mode for takeoff and landing and low speed operation and it operates in a ramjet mode in sustained supersonic flights. So you can see here that basically it is a turbojet engine placed inside the duct of a ramjet engine, okay.

So the outer one is a ramjet engine, this is a turbojet engine which is placed inside. The only difference is the turbojet engine now has a very extended intake. As we saw from our earlier discussion the intakes for turbojet and turbofan engines are usually very very small, practically nothing but in this case, the intake is quite extended because it is placed inside a ramjet engine.

So for low-speed operation, as you can see from here, the air comes in and it goes through the intake duct.

And these 2 flaps here, you can seem these 2 flaps, these are called bypass flaps. These 2 flaps are closed and the air is forced to go through the core turbojet engine. It goes through the core turbojet engine and then come out like this. So that is used for takeoff, landing and low-speed operations. When you reach supersonic flight speeds, these bypass flaps which were closed here as we can see are now opened.

So these are opened now and we can see that they shut-off the flow of air into the turbojet engine and the air now goes through this. So it is compressed in the intake and this, it is compressed in the intake here and then it goes through these passage, fuel is added, there are flame holders, combustion takes place and the air comes out of the nozzle like this. So this is the ramjet mode of operation, okay.

So the bypass flaps are used to switch between turbojet operation and ramjet operation. Couple of instances we can probably give couple of examples of applications where this technology was used, one famous example is of course the Concorde, supersonic transport aircraft which is no longer in service.

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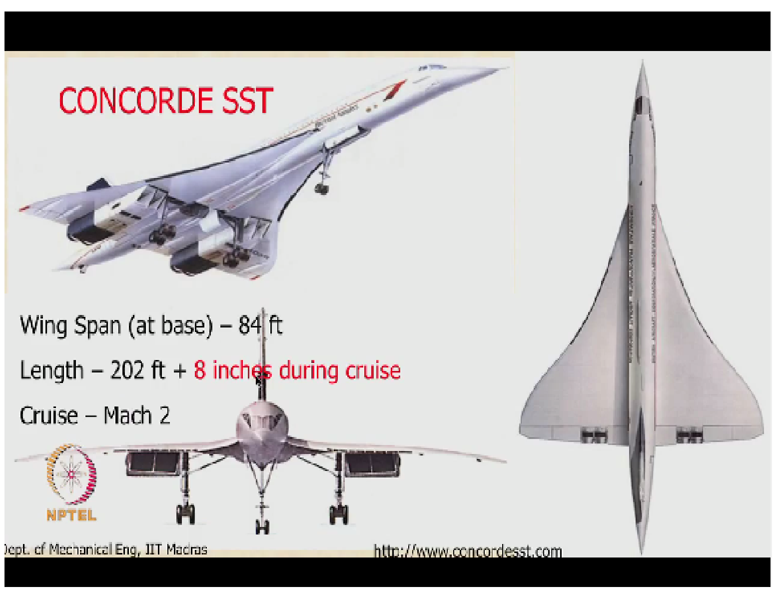

This uses a turboramjet engine, okay. So we can see the 4 engines here and we can see the rectangular intakes. Notice that the intake is rectangular but the engine itself is axisymmetric, okay. So it uses the rectangular intake to capture the air and compress it in the ramjet mode to feed into the ramjet part of the engine, okay. So you see 4 Olympus engines which look like this. The sustained cruise Mach number is 2 or so for this aircraft, okay.

And as I have indicated here, the planes length does change during flight. It expands and contracts significantly during flight by as much as 8 inches. All supersonic aircraft have the problem. The thermal expansion of the airframe can be considerable and you have to design the aircraft for that. This is only 8 inches. The SR71 expands even more, I will show that next.

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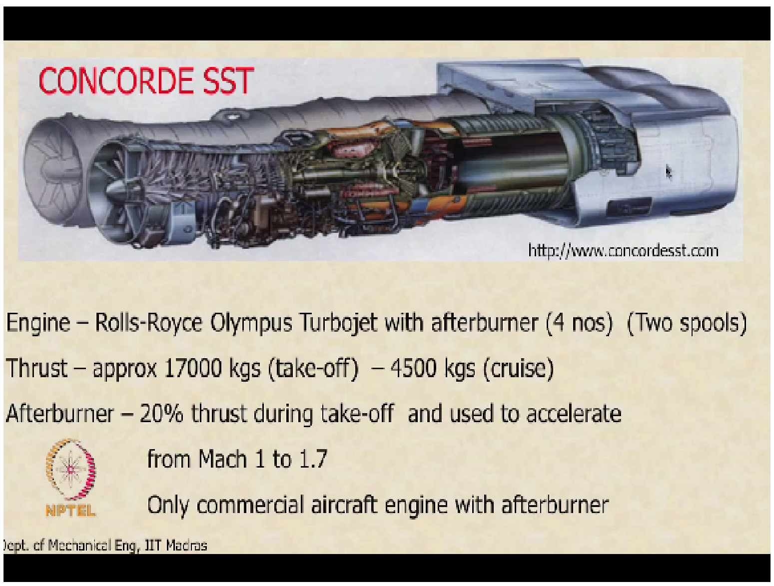

So here is a look at the Olympus engine. So it was manufacturer by Rolls-Royce, 4 engines were used each with the 2 spools and it also has the unique distinction of having an afterburner also because if you look at this picture, in the turbojet mode of operation, notice that we still have a lot of duct length that is available. So this duct can actually be used as a afterburner, okay. This afterburner is used in the Concorde and in other aircrafts to punch through the sonic barrier to reach supersonic speeds.

Usually going through the sound barrier increases the drag tremendously, so it requires a lot of power. So this can be used as an afterburner also to take the engine or to take the vehicle through the sound barrier. So in that sense this is turbo afterburning ramjet engine, if you include all the features, this is a turbo afterburning ramjet engine and that is what the Concorde also uses, okay. The afterburner is used for takeoff, it is also used to accelerate through the sound barrier to attain the supersonic flight speeds. It is the only commercial engine with an afterburner and the ramjet engine.

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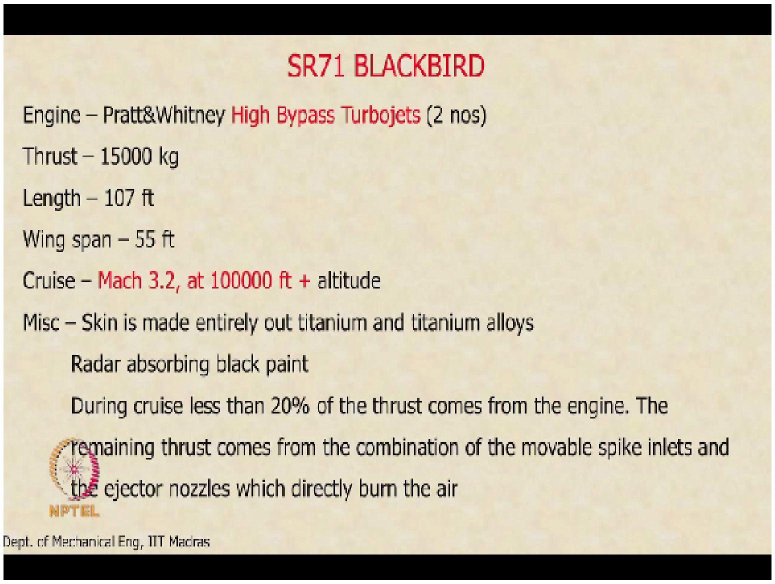

The next famous example of the use of turboramjet engine is of course the SR71 Blackbird, okay.

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So the Blackbird looks like this. This is a trainer version as we can see from here. This is the trainer version because you see 2 cockpits. The actual flight configuration of the vehicle has only 1 cockpit. The 2 cockpit shows that this is a trainer version and we can see that the airframe itself is revolutionary in design. The entire airframe is a lifting wing, okay. So here the aerodynamics itself is very challenging aspect. So you do not design the fuselage and then the wing.

The wing is designed and then everything is put inside the wings. So the entire body is a lifting wing, okay. So you design the aircraft outside in, not inside out. So you design the outer envelope and then put everything inside it, okay. So all surfaces in these aircraft are lifting surfaces. So we can see the very revolutionary design and it looks almost like a bat. So it is inspired by aerodynamics of a bat.

And you see 2 axisymmetrically configured turboramjet engines here, right and you see the spike or the centre body and the ramjet engine here. Let us look at the specs of the ramjet engine. These were manufactured by Pratt & Whitney in this Skunk Works facility or the engines were manufactured by Pratt & Whitney, the aircraft itself is a built in the Skunk Works facility by Lockheed Martin, produces a thrust of about 15,000 kilograms which we need to multiplied by 10 to get the thrust in Newtons.

Now this aircraft, actually the details are classified but supposedly it cruises at Mach 3.2 at altitudes of around 100,000 feet or so or 100,000 feet plus. It was very revolutionary when it came out because the skin is entirely made out of titanium and titanium alloys. So first time titanium was used in aircraft manufacture. The challenge was that titanium has very nice properties as we said earlier, is very strong, is very light.

But it is exactly those properties that also make titanium very difficult to machine. If it is extremely strong, it is also very difficult to machine, right. So Lockheed had to figure out revolutionary ways or new ways of machining titanium to the required shapes, it is extremely difficult to do. The entire vehicle is coated with radar absorbing black paint, so it has no radar signature and during cruise, only 20% comes from the turbojet part of the engine.

The remaining 80% comes from the ramjet engine, okay. This holds almost all aviation records that you can think of, fastest transatlantic crossing, fastest flights from New York to Los Angeles. It has broken all the records and it has been retired from service, it is a revolutionary aircraft.

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Here we can see the aircraft taking off from the Edwards Air Force Base. You see the exhaust diamond. If you recall during our gas dynamics course, we looked at these types of alternating expansion and compression fans and shock diamonds. We can see them very clearly here in this picture. You can also see the afterburner is lit. So this takes off with the afterburner lit and you see these kinds of mysterious puffs of stuff coming out.

This is actually fuel. So the SR71 actually leaks a lot because you have to account for thermal expansion of the vehicle when it is cruised. So it is designed to cruise at a certain Mach number. So when it is at the ground level, the parts actually do not fit very nicely. So it leaks a lot of fuel which is why it is not fuel fully when it takes off. The tanks are fuelled only partially for it to take off and reach altitudes of about 30,000 to 35,000 feet where it is refuelled in air.

And then you can fly to reach the higher altitudes because the parts do not fit very well at ground level for the SR71, and that is the problem you have to live with. So it is a very revolutionary aircraft when it was designed and when it was in service and even after it is retired, it continues to be a very interesting aircraft configuration, okay.

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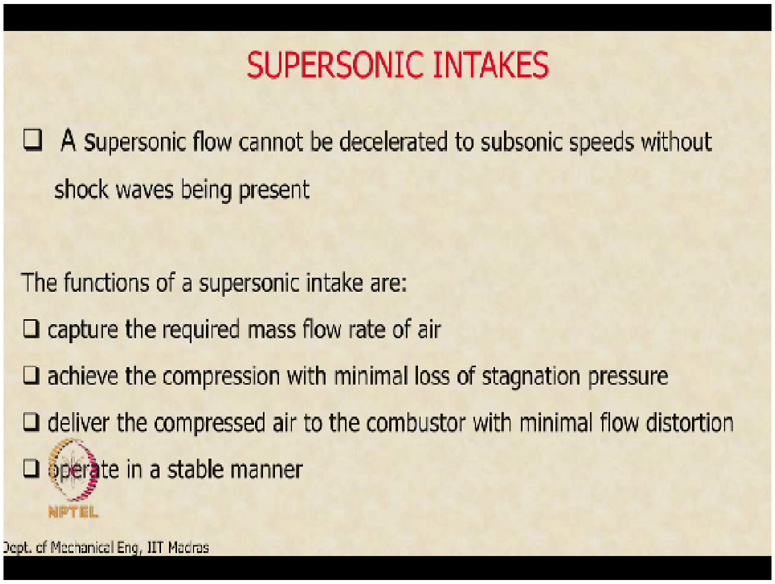

So now we can clearly understand that the supersonic intake is the most critical part of the ramjet engine, okay. So we will take a closer look at the intake of the ramjet engine. Of course, we know this from our gas dynamics, we cannot decelerate a supersonic flow to subsonic speed without shockwaves being present. You may think that, you know, if you send it through a converging-diverging nozzle, we can do this.

But even in a converging-diverging nozzle, if you look closely, although you do not see it, if you look closely, you will notice that each turn of the outer and inner wall producers a Mach wave if designed properly. So you cannot compress without waves being present. Mach waves are of course infinitesimal weak shockwaves. So you cannot actually compress a supersonic flow without using shockwaves in some form or other.

If you are using an isentropic compression waves, then intake is going to be very long. If you use oblique or normal shock, you can reduce the length of the intake, that is the only difference but there is no getting around the fact that there are going to be shockwaves present and the functions of a supersonic intake are given here. Number 1, capture the required mass flow rate of air.

The intake has to be designed so that we get the amount of air that we need for combustion and the most important thing, achieve compression with minimal loss of stagnation pressure because we do not have a compressed air, we are not putting in work to increases the stagnation pressure which means there should be no loss of stagnation pressure or as little the loss of stagnation pressure as possible in the compression process which means irreversibility should be kept to a minimum in the compression process.

And then it must also deliver the compressed air to the combustor with minimal flow distortion. By flow distortion what I mean is, if you take a section of an intake and you look at the variation of total pressure across this section, typically out of this intakes, the air comes out with a lot of distortion because you have shocks which are not fully 3-dimensional, which are 2-dimensional, so you have local pockets where the stagnation pressure can be low and local pockets where the stagnation pressure can be high.

So this kind of variation of stagnation pressure at a cross-section is called flow distortion and this can cause a lot of disturbance into the combustor because the combustor is designed assuming the uniform inlet flow condition, okay. So when you get a non-uniform flow like this, it can adversely affect the operation of the combustor, okay. So we must minimise the distortion at the exit or the intake before the flow goes into the combustor.

And you must also operate in a stable manner. Stability is a very very difficult issue with the supersonic diffuses. We have already seen that, right. Distorting shock causes a lot of problems in stability issues. So stability is a vexing issue with many of these supersonic intakes. It is no getting around it, we have to learn to live with it.

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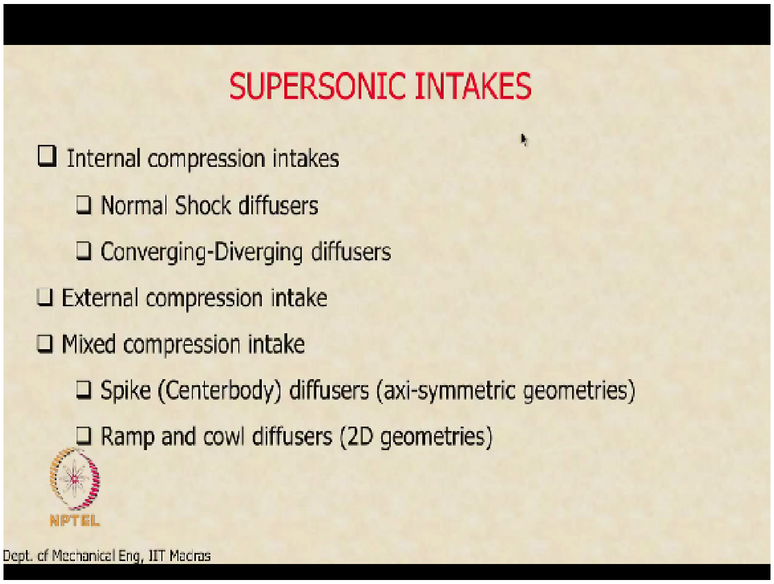

So the supersonic intake itself can be divided into 2 categories depending upon how we achieve the compression, okay. The internal compression intake achieves a compression in internal passages, properly shaped passages which will decelerate the air from supersonic to subsonic Mach numbers with increase in pressure, that is internal compression. External compression intake will use a series of properly designed ramps to generate oblique shocks to decelerate and compress the air.

Mixed compression uses both these, a combination of these 2. Part of the compression is achieved externally, part of the compression is achieved internally. In the case of axisymmetric geometry, the centre body is also called a spike along with a cowl which is the outer envelope. In the 2-D case, we use ramps and cowls. In the case of 2-D geometry, like the Concorde, we use ramps and cowls. In the case of axisymmetric diffuses, we use movable spikes and cowls.

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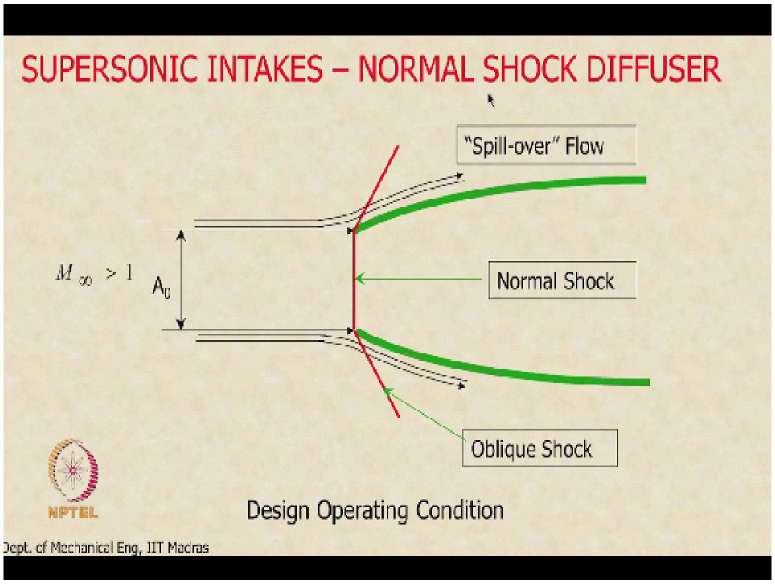

So let us start within internal compression intakes. So here we are looking at a normal shock diffuser which is something that we had already seen earlier. Now we can take an even closer look at this normal shock diffuser. So as we can see, the normal shock diffuser is really not a supersonic intake because it has a diverging passage and as you know, only a subsonic flow can be decelerated in the diverging passage.

So it is really only subsonic intake, pretending to be a supersonic intake because if you use this in a supersonic situation, normally as we saw earlier, you will have for example a bow shock which sits like this with a big normal shock portion to it and with 2 curved oblique shocks at the either end. So the flow goes from supersonic to subsonic across this and then the flow is diffused in the diverging area passage. This is the design operating condition for this intake.

If the Mach number is flight Mach number is not going to be significantly above 2 or if it is not even going to be close to 2, then we can use this type of intake because it is very simple in design and also interestingly enough, quite stable in operation, okay. Notice that for the design operating condition, the capture which is the cross-sectional area of the stream tube in free stream. The capture area is equal to the intake are because there is no deflection of flow around the intake.

If you look at the streamlines, the streamlines approach the intake like this and they enter like this. So the capture area is equal to the intake area for design operating condition. Now because we are talking about stability, we need to look at off design operating condition. What if the mass flow rate requirement of the engine is less than the design value or if it is more than the design value, what happens to the fluid dynamics or gas dynamic aspects of the engine. That is what we need to look at.

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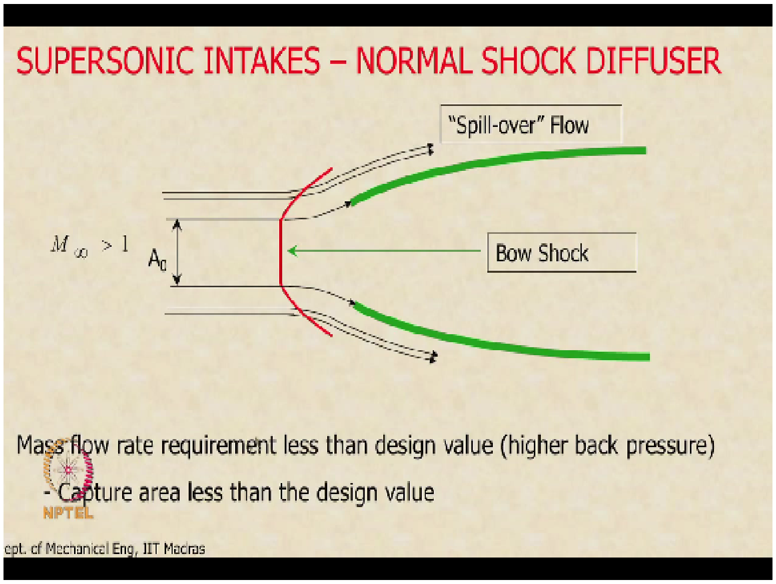

So if the mass flow requirement is less than the design value, meaning the pressure here is actually more than the design pressure. So I have increased the pressure in this part of the engine or if I want less mass flow rate in this part of the engine. If I want less mass flow, then under design condition, I am swallowing a certain amount of mass flow rate. If I want less than this, this means somehow the mass that tries to enter the engine has to be spilled around the engine.

You have to spill the mass flow rate around the engine. So reduced mass flow rate requirement here automatically translates to higher back pressure. So the higher back pressure will have the tendency of pushing the normal shock which was located at the lip of the diffuser here. It will push the normal shock further out depending upon how high the back pressure is. So once that happens, notice that the capture area automatically reduces (()) (31:33) capture area was like this, it was this much.

So you can see, some of the streamlines which are coming through like this, they would have just gone straight in the previous case of the design condition. Now because there is an oblique shock here, the air is deflected by this oblique shock, which means the air is now spilled around the engine. So that streamline or that portion of the stream tube which would have otherwise entered this engine, now is spilled around the engine, that is why it is called spill-over flow. So only this part of the stream tube which passes through the normal shock enters the engine like this, okay.

So automatically we can see that the mass flow rate has reduced. Assuming that, the free stream Mach number remains the same and we have reduced the mass flow requirement here or increased the pressure here. The cross-sectional area goes down and since the free stream conditions, static condition remains the same, automatically the mass flow rate through the engine also goes down and the capture area now is less than the design value.

This is also actually stable, there are no issues. This is how the engine will operate. What happens if the mass flow rate that I require here is more than the design value, right that is next.

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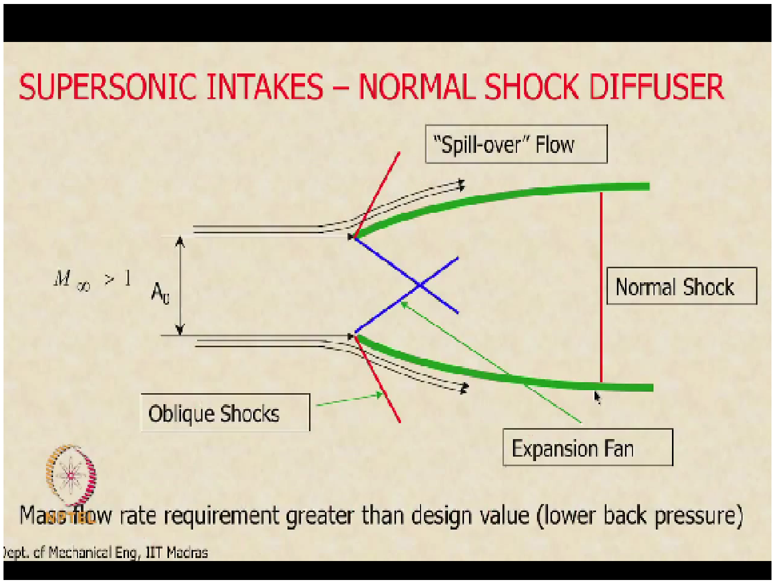

So if the mass flow rate that I require here is more than the design value which means I have lowered the back pressure some more. That has the effect of, what does that do. When I increase this pressure that had the effect of pushing the normal shock out. When I reduce the pressure here, what will that do. They will pull the shock inside unfortunately. When that happens, we can see that we have a supersonic flow, it comes like this.

This part of that oblique shock or the bow shock remains as the flow is deflated around this concave corner. Remember, this is the concave corner. So this 2 shocks in red will remain. The normal shock portion of this bow shock is pulled inside but now, this is a convex corner for the supersonic flow. So as the supersonic flow enters, it accelerates around this convex corner. So you this expansion fans.

So now this normal shock when it occurs, it is now occurring at a value of Mach number which is higher than the free stream Mach number, right, which means this shock is going to be stronger and the loss of stagnation pressure will also be stronger, okay. So as we can see from here when we go from, I am sorry, when we go from design operation, this is design operation, we have a certain amount of mass flow rates, certain loss of stagnation pressure, okay.

When I go from that to this type of situation where I have lesser mass flow requirement, then the mass flow rate reduces and the loss of stagnation pressure will more or less be the same or maybe even slightly less than before, right. More or less is same or less than before. So mass flow rate and loss of stagnation pressure will have a certain value. Now when I reduce the mass flow rate, the mass flow rate reduces, the loss of stagnation pressure remains the same or reduces slightly.

If I increase the mass flow rate requirement, then mass flow rate may increase slightly but the loss of stagnation pressure, what happens to that? That actually now increases much more. So the loss of stagnation pressure now is much more. This is typical of any supersonic intake, okay. The first mode of operation for which it is designed is usually called the critical mode. Lesser mass flow rate requirement is called the subcritical mode when the mass flow rate is less but loss of stagnation pressure is more or less the same.

Supercritical mode is when we need more mass but that is accompanied by very high loss of stagnation pressure. So we will look at this later on when we draw the operating characteristic for a supersonic intake. **"Professor - student conversation starts**" Yes. Sir in supercritical mode, mass fluid, mass flow rate is same as design mass flow rate. More or less, it will be same as design mass flow rate. There will not be too much… capture area is the same.

So there will not be too much increase in mass flow rate for supercritical mode of operation. Even if you look at the actual operating characteristic curve, you will notice that the increase in mass flow rate is very little if you lower this pressure. For some intakes, it can be slightly more but not much more than that. Not much more than the designed value. When I show the operating characteristic of an intake, we will be able to see that point, okay. **"Professor - student conversation ends".**

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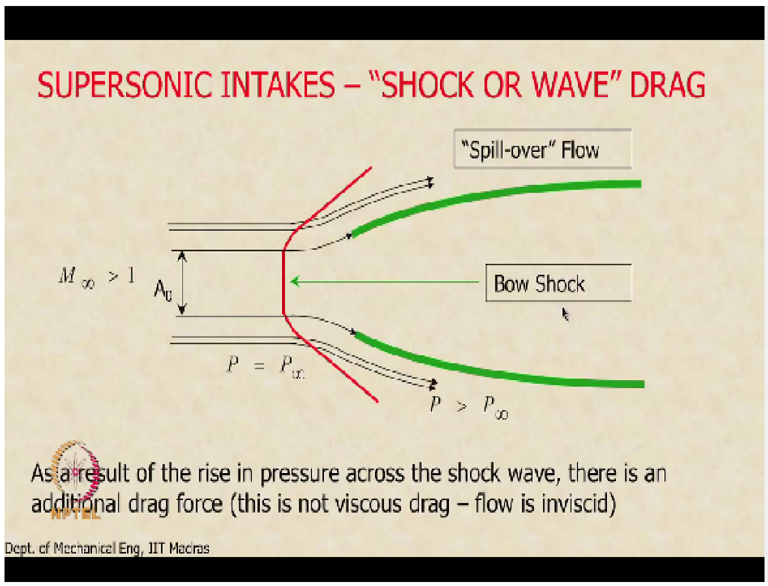

One additional problem with supersonic intakes is a new thing called (()) (36:26) drag or wave drag, okay. Remember we are still talking about inviscid flow, we are talking about gas dynamics, we are talking about inviscid flow. So this drag is not due to viscosity, it is due to gas dynamics or fluid dynamics if you will, okay. So as we can see from here when we have a diffuser which operates under off design condition or even on-design condition is also okay.

If you see this, we can see that as the air goes around this, right, the static pressure air is equal to the free stream static pressure but the static pressure here is now more than the free stream static pressure due to passage through the oblique shock. So because this static pressure is more now there is going to be a net force in the axial direction because this static pressure has now increased which means that there is going to be an increased drag force.

Remember the flow is from left to right. Here the intake is stationary, flow is from left to right. So drag force means force along the direction of the flow. If the flow is stationary and the intake moves, then drag force will be opposing the direction of motion of the vehicle. So you have to be very careful about the frame of reference, okay. So here the flow is from left to right, the intake is stationary.

So any net component of force in this direction is going to create increased drag. This is called shock drag or wave drag which is seen in supersonic diffusers. So the drag of the vehicle actually increases due to the presence of the supersonic diffuser and that is something that cannot be avoided. So we have to account for this also. So removing the compressor and turbine was a great great advantage but it is not without a price. The price comes in the form of these types of difficulties.

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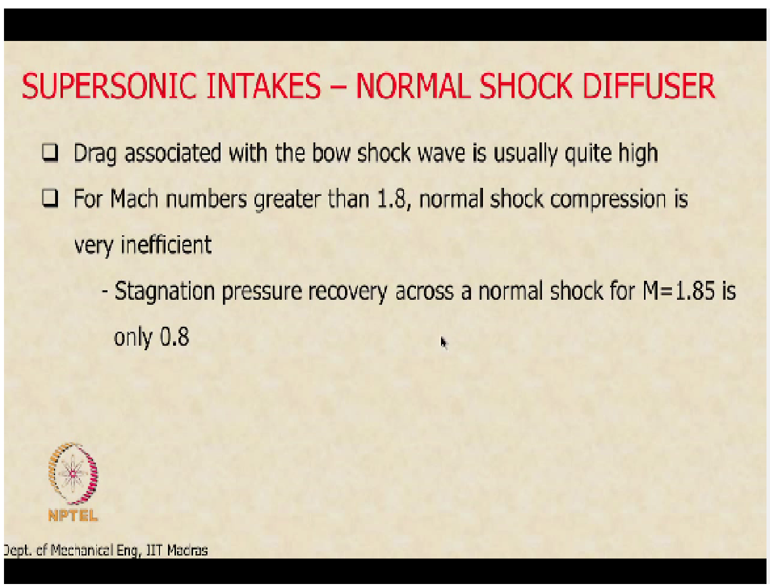

Now as we just discussed, the drag associated with the bow shockwave can be quite high, wave drag can be quite high, especially as the Mach number increases, the shock becomes stronger, the drag can be quite high and we saw in our discussion on normal shock that once the Mach number goes above 1.8 or so, normal shock compression becomes very inefficient, a loss of stagnation pressure becomes very high. It can be 20% for Mach number 1.85 and it increases very very steeply.

So the normal shock diffuser can be used only when your flight Mach number is no more than 1.7 or 1.8. So in all practical applications, it is not possible to use the normal shock diffuser because we cannot guarantee that the flight Mach number will be only 1.8 or so. It can be more than that and 1.8, it is not really very high for sustained supersonic flights. So the normal shock diffuser is very good for illustrative purposes but not really very practical, okay.

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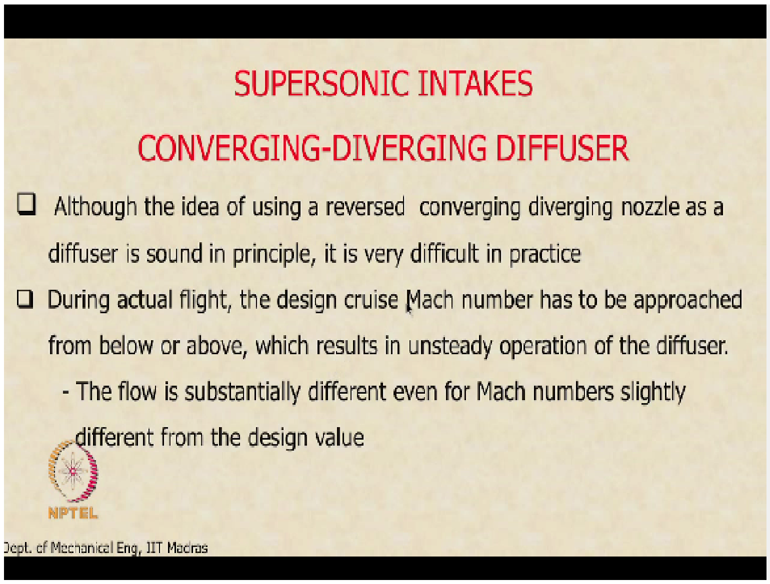

So the next type of internal compression intake is something that we already saw, a converging-diverging diffuser, okay. This also is a device which is very good in principle but almost impossible to realise in practice because of stability issues associated with it, okay. So what happens is, we will come back to this point after we go through this.

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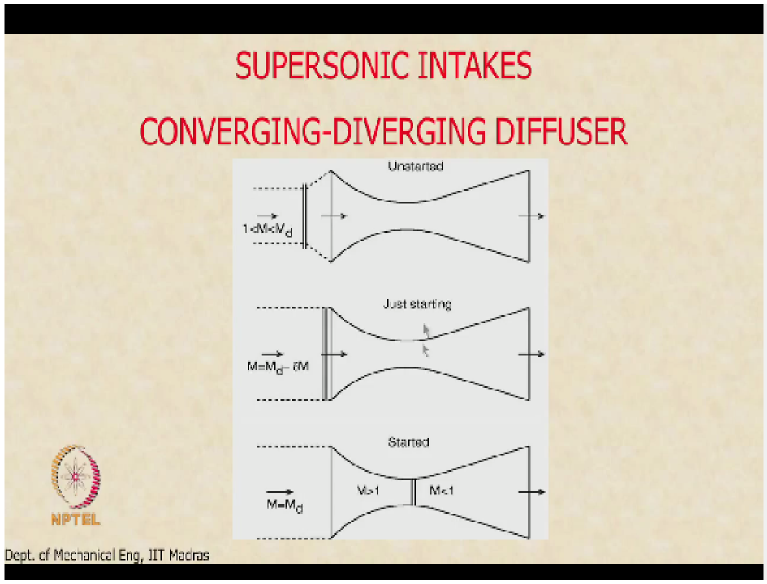

So here, we are looking at this converging-diverging diffuser when it is started up, okay. So as you keep increasing the flight Mach number, as we can see from here, initially there is a normal shock with 2 bow shock components which stand in front, just like the normal shock diffuser, right. So there is a bow shock component to this. So only the part of the stream tube which comes through this normal shock will actually enter the intake.

So the flow is then deflected, so it will come through properly here. So this is for a Mach number which is supersonic but less than the design Mach number M sub d. So this intake is said to be unstarted. In the terminology of supersonic intakes, we say that an intake is started when the flow field inside the intake is at the intended design condition. Now there are possibilities that you know you can have if you remember this types of flows can have 2 solutions, one which is completely subsonic, another one which is supersonic.

So the intended solution, when that is realised, that is when the intake is said to be started. It provides the required amount of mass flow rate at the designed value of stagnation pressure, that is when the intake is said to be starter, okay. So in this case, we can see that in a converging-diverging diffuser, we say that the intake is started when it has shock free operation but even in this case it has shock free operation but notice that this is not the intended flow field inside this which is why we say that this is unstarted, okay.

As I keep increasing the Mach number, now the Mach numbers is, flight Mach number is just delta M below the design Mach number. So this normal shock keeps moving closer and closer to the intake. Eventually it will stand at the intake lip. Once it stands at the intake lip, right, at design condition, this will stand at the intake lip and it will not move at all. So you may be operating at a design Mach number.

But there will be a normal shock which stands at the intake, just at the intake lip and the flow inside is completely shock free and that is the permitted solution for this flow field. So the normal shock will not budge. So the only way to get the normal shock to move is to actually get it to a Mach number which is higher than the design Mach number. So once that is done, then this normal shock will move rapidly and position itself at the throat where it becomes a very weak shock and the intake is said to be started.

So this is the situation when the intake is started. So you go to a higher Mach number, higher than Md, pull the shock inside and then you decelerate the intake slightly to the design Mach number and then it will operate like this. So it is not very easy to get this intake started. Even though it is designed for Md, when you approach this design Mach number from below, meaning from Mach numbers less than the design Mach number, you will not be able to attain this started flow state.

You will still have a normal shock sitting here. So you need to accelerate beyond the design Mach number, pull the shock inside and then come down to the design Mach number, okay. So that is the starting difficulty that we talked above, okay. So during actual flight, the design cruise Mach number has to be approached from below or above, meaning from a lesser value or lower value and this will result in an unsteady operation of the diffuser.

Even if there is a small fluctuation in inlet condition or in any of the conditions inside, the shock that was swallowed and sent to the throat will again be disgorged and it will go out and stand at the entrance to the intake and very small departure from operating condition will disgorge this swallowed shock. It will again stand at the intake. Once again you have to accelerate the vehicle to above design Mach number, pull it back inside and then come back to the design Mach number.

So the flow is substantially different even for Mach numbers slightly different from the design value. Notice that here, the Mach number is slightly different from the designed Value but you can see that the flow inside is substantially different, right. It is fully subsonic inside and again decelerating inside depending upon whatever you have here. Whereas design condition, fully supersonic here and subsonic here.

So you can see that there is a substantial difference in the flow field even for small changes in the design Mach number or small changes in the operating Mach number or operating flight condition, that is a major disadvantage because this is prone to instability. Even a small departure here will force this shock to be disgorged and it will stand at the inlet like this and it go through the cycle again and again. So you have to go through this kind of stresses cycle again and again.

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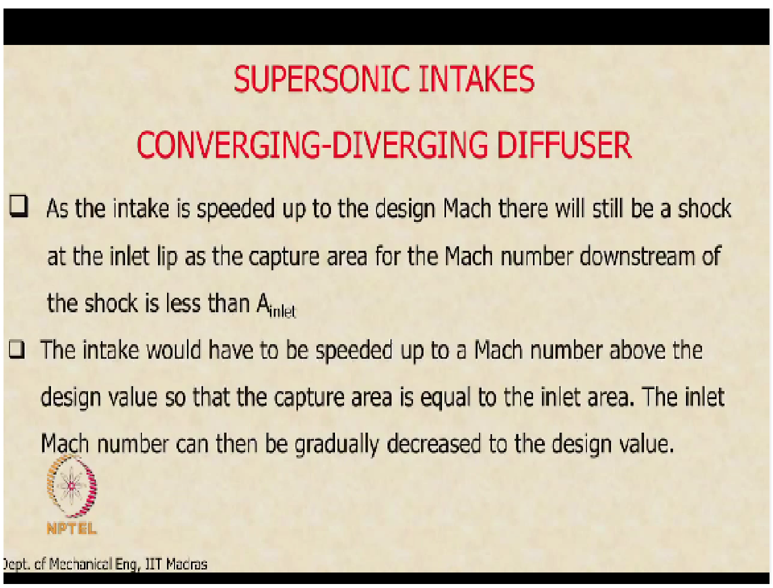

So this we have already discussed. So the intake has to be speeded up to a Mach number above the design value so that the shock can be pulled inside and then it has to be decelerated slightly, okay.

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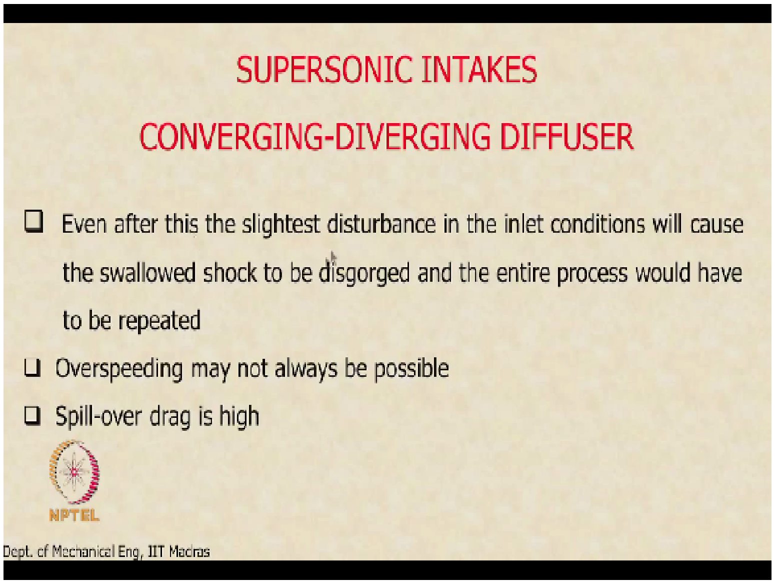

So it has stability issues and operational issues, okay and as we said even the slightest disturbance in the inlet condition, will cause the swallowed shock to be disgorged meaning the shock will come out and the entire process has to be repeated and spill-over drag is also quite high for these types of intakes, okay. So these are the 2 types of internal compression intakes that we can think of using. So what this means is that it does not mean that we have to discard these intakes.

What it means is that, we have to find a suitable operating point or design condition or operating condition for these intakes, right, that is what we will see as we go along. There are advantages to this. So we should think of using these disadvantages also and we will see that the best design utilizes external compression partly and internal compression partly, that is the best way to utilize these intakes, not use them in their entirety, produce them for accomplishing part of the compression process, okay and that is what we are going to see in the next class.

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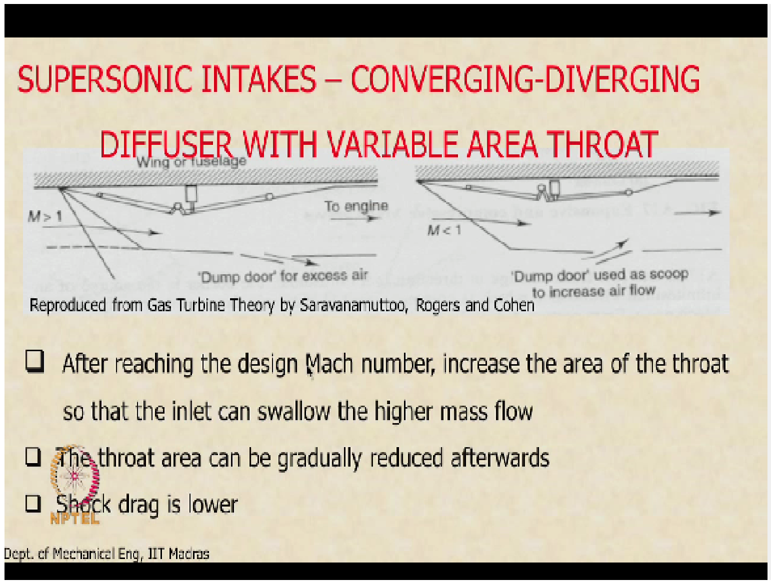

So here we can actually see some of these types of internal intakes which have been used. So this is the internal intake that is used for example in the Concorde, one way of getting around this issue of going up and down. We will discuss this in detail in the next class. How do we address the problems of these diffusers so that they can be realised in practical application, that can be used in practical application that is something that we will discuss then move on to external compression intakes in the next class.