**Jet Aircraft Propulsion**

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**Lecture No. # 29**

**Nozzle: Fixed and Variable Geometry Nozzles**

Hello and welcome to lecture number 29 of this sound going lecture series on jet aircraft propulsion. As we have been discussing so far, we we have been talking about different components of jet aircraft engine. We have covered sufficient ground in terms of discussing various aspects of the different components which constitute a jet engine. We have so far discussed about the compressors, the different types of compressors, then the combustion chamber, the turbine, and then last couple of lectures we have discussed about the intakes.

Now, the last component that we are going to discuss about is the nozzle. Nozzle, in fact also forms the last component of a jet engine, if you look at the air flow, right from the intake through the compressor through the combustion chamber, the turbine then with or without afterburner ending in a nozzle. So, all jet aircraft engines have nozzle as the last component, which constitutes the entire jet engine, and so nozzle is also very important component of the jet engine. In fact, all the components which constitutes jet engine have their own very significant role to play in the overall performance of the engine. Nozzle also has a very important role to play in the performance of the engine. So, what we are going to discuss today is what are the functions of nozzles? What are the various types of nozzles which are in existence.

And we will also look at some of the additional functions with some of the modern day nozzles have to perform like thrust reversal, and thrust vectoring, and noise control, and so on. So, we will just have an overview of some of these aspects during today's lecture. We will continue our discussion on nozzles in the next lecture as well; wherein we will discuss about the different functions, and the performance parameters of a nozzle. We will also look at how different are subsonic and supersonic nozzles, in fact the operation of these two different types of nozzles are entirely different. We will also look at how these nozzles perform, and what is in that we need to keep in mind when design of a nozzle is taken up. So, in today's lecture we are going to discuss about these following topics.

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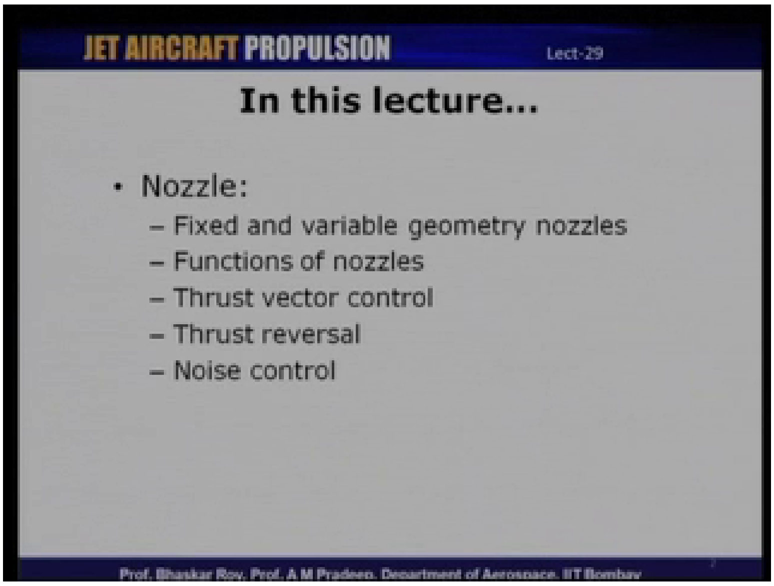


We will be talking about two types of nozzles; two broad classes of nozzles, the fixed and variable geometry nozzles. We will be talking about the functions of the nozzles. We will also talk about some of the additional functions with some of the modern day nozzles are performing like thrust vector control, thrust reversal, and noise control. So, in today's lecture, we shall be discussing about some of these topics in general. We will not be going into very in depth discussion on some of these topics, which is probably out of scope of this current course. But in the next lecture, we will take up discussion in some detail about the performance parameters.

Now, perhaps you must have realized by now that the basic function of a nozzle is that it converts the pressure energy that is available after the turbine and the tail pipe and so on; that is converted into some form of kinetic energy and the jet exhaust that comes out of the nozzle produces the reaction thrust. So, in some sense, the thrust which a jet engine produces is primarily because of the nozzle exhaust creating the reaction effect, which means that in those engines which do not require or do not or not required to produce any thrust will not really have a nozzle in in the classical sense. For example, all gas turbine engines which are used for power generation in thermal power plans.

They obviously do not required to produce any thrust and therefore they do not really have a nozzle, the way an aircraft engine has. They do have an exhaust system; but it is not a nozzle.

It does not generate any thrust like a put in an aircraft engine. Basically because in align based engine, you do not require any thrust; you only require to convert the turbine work output to drive a generator, which will give us the electricity; whereas in an aircraft engine, the function is entirely different. The turbine is meant only to drive the compressor and may be some accessories. But the primary function of an aircraft is to produce a reaction thrust and that comes primarily from the nozzle, which converts the energy that is available at the nozzle entry into jet exhaust which generates a thrust.

So, generating thrust is the primary function of a nozzle in a modern day jet aircraft. But that is not all; many of the modern day aircraft nozzles have many other functions, which are probably as important as generating of course generating thrust will still remain the primary responsibility of the nozzle. But besides that, there are other functions. For example, in a military aircraft, some of the modern day military aircraft have what is known as thrust vectoring. That is, the thrust is vectored or deflected in a direction which is different from its primary direction; in which case if the thrust is different from its actual direction or horizontal direction that will deflect the aircraft in the desired way.

So, thrust vectoring is one way of achieving maneuvers or climb rates which are impossible to achieve with conventional control surfaces and that is why, the that is another function of modern day nozzles that it will also give us thrust vector. The other function is when an aircraft lands; that is modern day aircraft are becoming bigger and bigger in terms of its size as well as weight and therefore, stopping or braking an aircraft with conventional wheel brakes is no longer sufficient, you need additional means of braking an aircraft after it has landed. So, thrust reversal also is another function of nozzles; that is the nozzle exhaust is deflected.

So, that you get a component of thrust which is in the forward direction and therefore, that will help us in braking the aircraft much quicker than it would be by using conventional brakes; that is another function of nozzles. Then of course there are other functions like noise control and infrared radiation control. Noise control is important for both military as well as civil aircraft and the different concepts which have been tested and developed; so that the nozzle geometric can be slightly modified and altered. So that the jet exhaust noise can be kept under control. Infrared radiation suppression is also important for military engines, where you would not like the aircraft plume; that is the jet aircraft exhaust plume to be detected by the enemy radar.

So, you would like to have as low an infrared radiation from the jet exhaust as possible. So, this is also possible by providing or by modifying the exhaust geometry; the nozzle geometry. So, that the jet exhaust plume has much lower infrared sig infrared signatures. So, these are some of the broad functions of a nozzle. We will also look at some of the details of what else the nozzle would have to do. If some of these function have to be satisfied that is in the process of satisfying some of these functions, it must not alter the performance of the engine as a whole and that is to be ensured by very careful design of the nozzle which is very (( )) very essential, if the nozzle performance has to be in sync with the engine performance as a whole.

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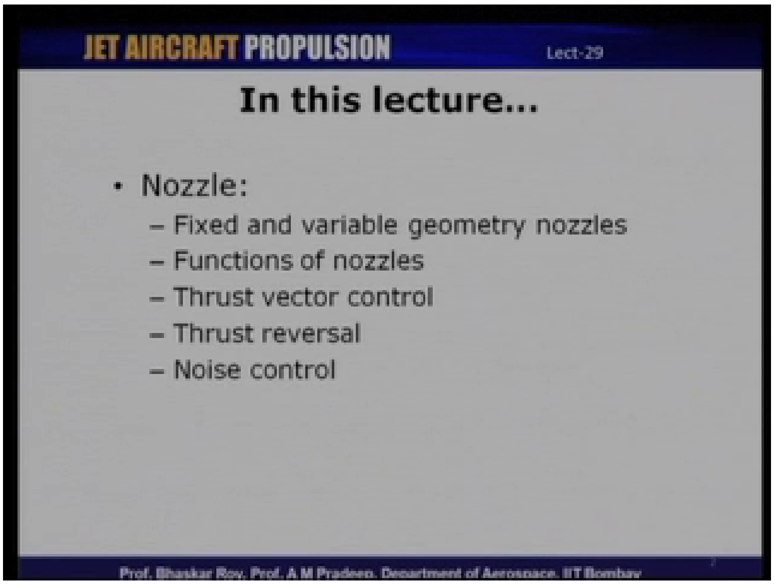


So, let us look at what are the different functions of a nozzle; what are the different types of nozzles and where these different types of nozzles are currently used. So, we will begin with some overview of nozzle as such and then we will proceed towards classifying the nozzle in to different categories. And then we will understand the different types of nozzles and also the other functions of the nozzles like thrust reversal and thrust vectoring and noise control. So, nozzles are as I said primarily, the thrust generating mechanism in a jet engine in most of the jet engines; for example, in turbojet or turbofan engines. Whereas in turboprop engines, some of the engines may have jet thrust; some of them may not have thrust.

Because in turboprop engines, the major chunk of the thrust that is developed by the engine is because of the propeller. Of course, the nozzle also may contribute to the overall thrust development; but that may usually be a smaller fraction has compared to be overall thrust; because the propeller generates the majority of the thrust. Whereas in pure jet engines, the turbojet and the turbofan; it is the nozzle which generates the thrust. And so it becomes all the more important to look at nozzle geometries for such type of engines. Besides this, if you look at a subsonic aircraft and the supersonic aircraft, the nozzle geometries are quite different.

Because we know that in a converging nozzle or converging duct, the maximum mach number that you can achieve is about mach 1; that is at the throat that is jet exhaust at the exhaust area, you get the maximum mach number which is the sonic mach number. And beyond that, if you need to still accelerate and achieve supersonic mach number, a convergent nozzle would not serve the purpose. One would have to go for a convergent-divergent nozzle. And so in supersonic intake supersonic aircraft normally would have a convergent-divergent nozzle, which will help us in achieving supersonic mach numbers something which is not really possible using a convergent nozzle.

So, supersonic and subsonic intakes are entirely different. Besides this, the nozzle geometric can either be fixed or it could be variable; that is if it is a fixed geometry nozzle, then the nozzle cannot really accommodate too much change in mass flow rate; because it will normally be operating under choked condition, which means the mass flow gets fixed. Therefore, if the aircraft has to operate over a variety of operating ranges, then a fixed geometry nozzle may not really serve the purpose; you may need to increase or decrease the nozzle area.

Which is why, there are variable area nozzles which are the preferred types of nozzles; which are used in usually in the military engines, where one has to operate over a variety of operating ranges including with after burning, where one may have to change the nozzle exit area and that that is possible by using variable area nozzles. Of course using or implementing variable area means there are additional mechanical complexities, which will have to be kept in mind. Because simple fixed geometry nozzle is easier to design; but it has its own limitations. Variable area geometry nozzles have additional functions or applications; but they are more complex and complicated to design and develop.

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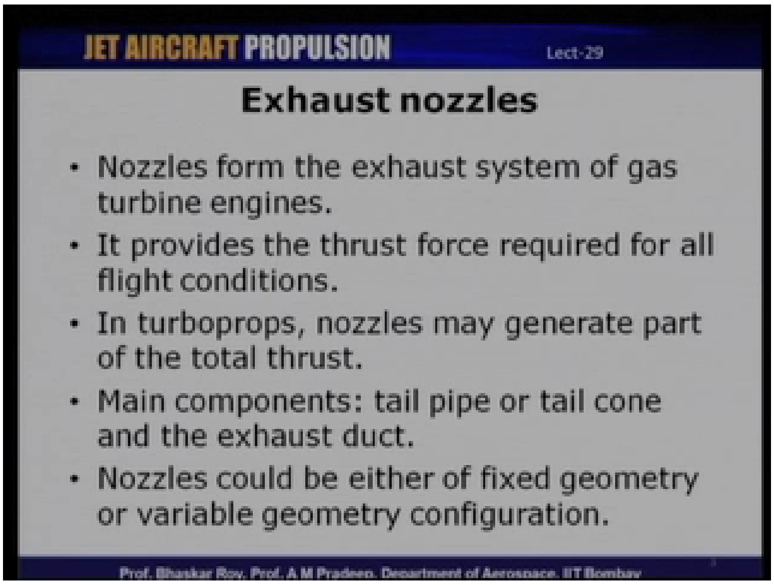


So, in a nozzle the basic function being exhaust, as if you look at the thermodynamic cycle, nozzles formed one part of the exhaust system and so nozzle is the probably the more important component of the exhaust system. There is also a tail pipe which precedes the nozzle that also forms the part of the exhaust system. Now besides that, the nozzle forming a part of the exhaust system provides the required thrust for all the flight conditions and in certain types of engines like in turboprops, nozzles may also contribute to the engine besides of course the propeller thrust. So, what constitutes a typical nozzle or an exhaust system?

Exhaust system basically consists of a tail pipe or a tail cone, which is from the turbine exhaust all the way up to the nozzle entry and ofcourse, the exhaust duct of the nozzle itself. And depending upon the type or the geometry of the nozzle, nozzles could either be fixed geometry or they could be variable geometry. So, nozzles can either have fixed geometry in some applications. Some applications demand that the nozzle geometry be be variable and that is very important especially in military aircraft, where the operating regimes can changes drastically especially when the aircraft is maneuvering or it has to accelerate to supersonic speeds and so on with afterburner. So, variable geometry becomes essential in such applications.

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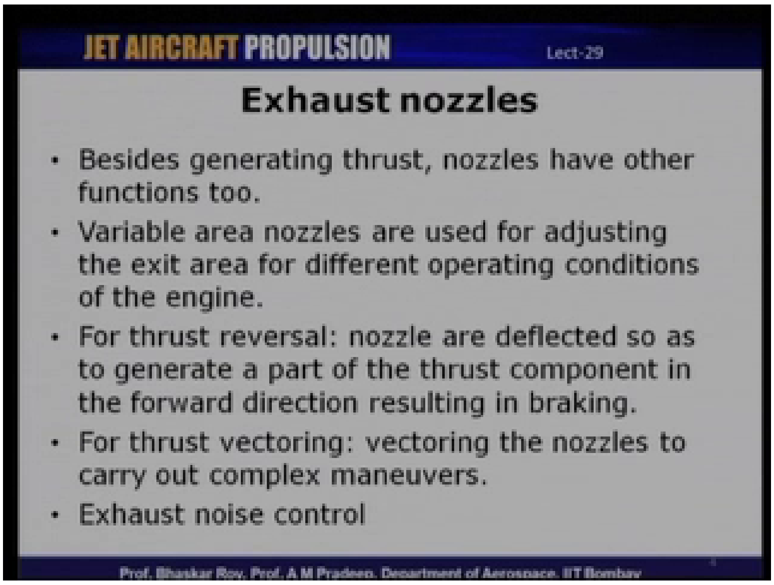


So, besides that nozzles beside generating thrust itself, nozzles have several other functions, atleast the modern day nozzles have several other functions as I have mentioned. Now, the variable area nozzles as I mentioned are used for adjusting the exit area for different operating conditions of the engine. Then the other function of a nozzle would be thrust reversal, as I mentioned thrust reversal is used in braking the aircraft or after it has landed, conventional wheel brakes may not really be sufficient to bring the aircraft to a halt within the given runway length. So, thrust reversal is used is this is one way of braking the aircraft quickly besides of course the wheel brakes.

So, most of the modern day aircraft both civil as well as military aircraft would have thrust reversal mechanisms; that is once the pilot lands or the aircraft has landed, the pilot would also deploy the thrust reversal. Once a thrust reversal is deployed that can lead to deceleration of the aircraft in much shorter length as compared to the conventional wheel brakes and this is very important in in some of the airport airports. The runway length may not be sufficient for the aircraft to halt before it exhausts the runway length itself. So, thrust reversal can really help in such applications besides ofcourse military applications; especially if it is a marine combat aircraft, it has to land on the on a fighter ship.

Then obviously, it has very limited runway length. So, over and above thrust reversal many a times they also use parachutes. Parachutes are deployed to brake the aircraft in shortest runway length is possible. So, besides thrust reversal which is sort of used also in civil aircraft, something that is very commonly used in military aircraft is the thrust vectoring. Now, thrust vectoring is one of the ways by which one can deflect the exhaust nozzle in a in a desired directions. So, that it produces thrust in a direction, which is not in the direction that it would normally produce. So, that once your thrust is in a different direction, the aircraft is forced to move in a direction which is different from what it was earlier moving.

So, thrust vectoring will help us in deflecting the aircraft carrying out maneuvers or having climb rates, which are much higher than what conventional control surfaces would be able to do us. So, as we know, the aircraft maneuvers are controlled by control surfaces in most of the aircrafts using ailerons or flaps and ofcourse, there are certain limitations or ranges between within which an aircraft can be maneuvered using the control surfaces. But by using thrust vectoring which is basically by deflecting the nozzles, one can achieve maneuvers which are beyond the limits given by the classical control surfaces.

So, using thrust vectoring, one can deflect and achieve very substantial amounts of maneuvers, which are not really possible using the control surfaces. So, that is another function of a nozzle modern day nozzle and then there is yet another function, which is also gaining very, very much significance that is in noise control. Because there are lot of very stringent noise regulating norms which are coming into existence, which is all which are already in existence in and which are getting stricter every few years. That is every aircraft or engine manufacturer has to ensure that the engine noise levels are kept under control and jet exhaust noise forms a very major part of the overall noise generated by an aircraft like the air frame.

An aircraft noise consists of different components like the air frame noise and the engine noise. Engine noise again is split into different other components like the turbo machinery noise coming from the fan and the compressor or the turbine and ofcourse, the jet exhaust noise. Jet exhaust noise forms a significant part of the overall noise. So, some of the nozzle geometries or atleast some of them which are being tested and which continue to be developed are having geometries, which are also made with an intent of having reduced jet exhaust noise; which is possible, if one can alter the jet exit area in such a way that the jet exhaust mixes very well with the ambient air.

And therefore, some of the modern day nozzle geometries also are required to keep noise levels under control. So, these are some of the functions of a nozzle besides ofcourse the primary function; that is thrust generation. As we can see, there are several other functions which a nozzle has to function basically to enhance the performance of an aircraft, besides ofcourse generating thrust. So, let us now look at different types of nozzle geometries and see the differences between these geometries and then we will try to analyze what are the ways in which one can classify nozzles based on the nozzle geometries and their applications itself.

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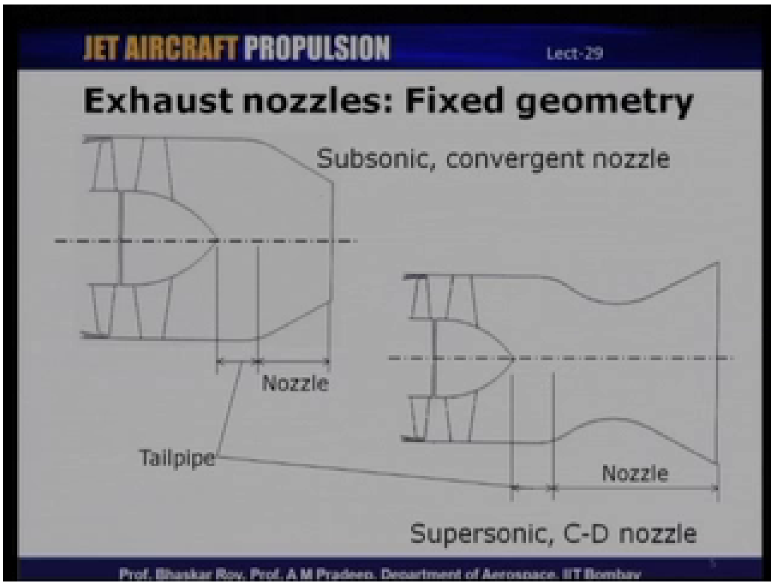


So, what I have shown here are two different nozzle geometries. One is a subsonic nozzle and the other is a supersonic nozzle. So, the first one that you see here is a subsonic nozzle. And so one part of the nozzle has I had mentioned is the tail pipe. Tail pipe constitutes one part of the nozzle and the nozzle itself. So, tail pipe is the component that is seen here that is right after the turbine exhaust and after the turbine hub ends all the way up to the entry of the nozzle. This is usually referred to as the tail pipe and then we have the nozzle itself. So, a subsonic nozzle typical subsonic nozzle is convergent that is the nozzle geometry or the nozzle area decreases axially.

So, as we move along the axis, we can see that the nozzle area is decreasing. So, this is a typical subsonic convergent nozzle and as I mentioned already, this has a certain limitation especially we have to have supersonic flight, supersonic mach numbers; such type of nozzles will not suffice we need. Because in this case, the mach number at the exit is limited to unity. So, you just get sonic mach number at the exit. It is not possible to get supersonic mach numbers here. So, if one has to really go for supersonic flights, then we need to really change this geometry and have what is known as a convergent-divergent nozzle; that is a C-D nozzle.

So, this is typically a supersonic C-D nozzle and that is a C-D nozzle; because we have a convergent section here; that is the throat, where we have the minimum area and after the throat, there is a divergent section. So, convergent and the divergent section put together forms what is known as a C-D nozzle or convergent-divergent nozzle used commonly in supersonic aircraft, if the aircraft has to fly at supersonic speeds and a supersonic nozzle also has a small section known as the tail pipe. Now, both these geometries as you can see as I mentioned here are fixed geometries. That is, both these geometries the subsonic convergent and the supersonic C-D nozzle both are fixed.

So, these geometries cannot be changed depending upon the operating conditions. But this is a disadvantage in sense that in some cases, you may to want to really operate at different operating conditions and since the nozzle geometry is fixed, the mass flow is also fixed. Because the choking mass flow at the exit will fix the mass flow and therefore, the aircraft operating range can be limited. So, one may require a variable now geometry, especially if the aircraft has an afterburner. So, in the presence of an afterburner, one might definitely need variable area nozzle. Even in a normal engine, one would desire to have a variable area nozzle so as to have a greater flexibility in terms of range of operation.

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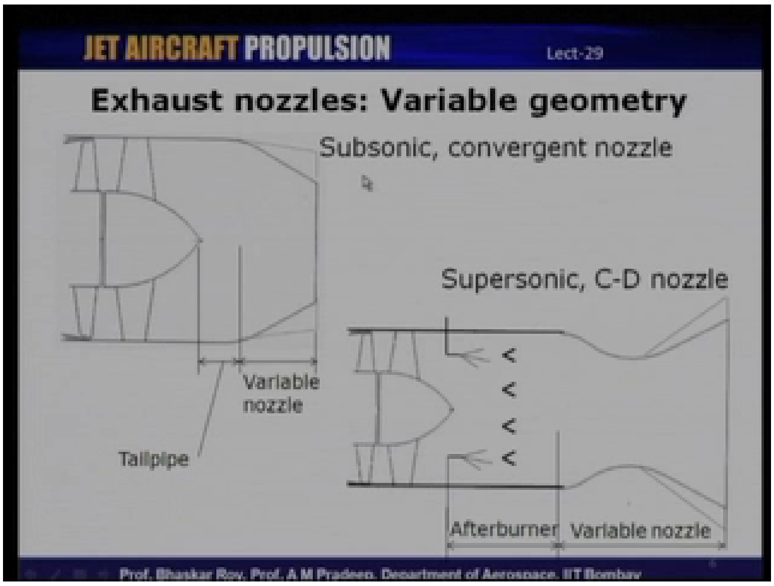


So, the other type of nozzle would be the so subsonic and the supersonic. Ofcourse, both of them in the variable geometry nozzle; that is the nozzle geometries can be varied. In the previous slide, there I was showing you fixed geometry nozzles. These are variable geometry nozzles; wherein, the exit geometry can be varied; the area can be varied and their different mechanisms by which one can achieve variable geometry. We will discuss that shortly. And in a supersonic nozzle, usually the variable area nozzle is used if one has an afterburner. So, the tailpipe as was shown earlier is basically an afterburner in this case, where one would add additional fuel and this results in additional thrust which is especially required, when the aircraft has to fly to supersonic mach numbers.

So, in the presence of an afterburner, the fixed geometry C-D nozzle will would simply not suffice. One would need to vary the area especially; because the the pressure upstream of the nozzle has change substantially and that can be accommodated, only if the nozzle exit geometry can be varied. So, a variable geometry nozzle is essential in in such applications. So, these are two different types or classes of nozzles; the fixed geometry nozzles and the variable geometry nozzles. Besides this ofcourse, there are other classifications that we are going to quickly look at. And we will see that there are are other types or classes of nozzles; the different ways in which you can classify nozzles, besides ofcourse being fixed or variable.

Now, one classification is something I have already mentioned that is convergent type or convergent-divergent type. That is convergent nozzles are usually used in subsonic mach numbers. If we need to fly to supersonic speeds, one has to go for a C-D nozzle or a convergent-divergent nozzle and then we have the nozzle, which could either be axisymmetric or it could be two-dimensional. An axisymmetric nozzle is one which is symmetric along the axis; it normally circular in in geometry. Two dimensional nozzles can be rectangular and so these are two other types of nozzles which can be used. And some of the earlier generation aircraft had two-dimensional nozzles especially meant for thrust vectoring. But some of the modern day aircraft also have axisymmetric nozzles, which can be vectored and you have you can achieve thrust vectoring even by using an axis symmetric nozzle.

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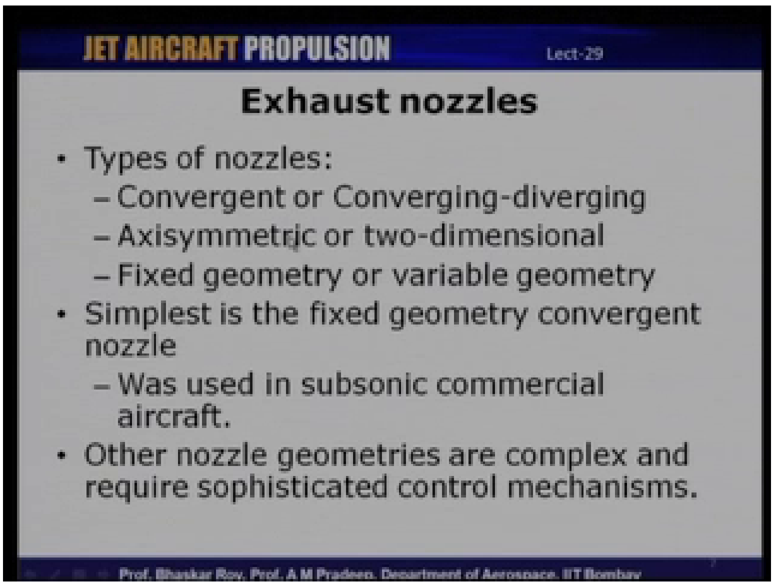

So, the types of nozzles would be convergent-divergent or converging or it could be axisymmetric or two-dimensional; could be fixed geometry or variable geometry. Simplest of these or the of these different types is the fixed geometry convergent type of nozzle have already shown the schematic of that. It was used in subsonic commercial aircraft. But it has lot of limitations in terms of it is ability to operate under various operating conditions. Now, the other types of geometries wherein one has to have a variable geometry or convergent-divergent; all of them are slight much more complicated than the simple fixed convergent nozzle. And also if one has a variable geometry, it will require sophisticated control mechanisms to vary the area.

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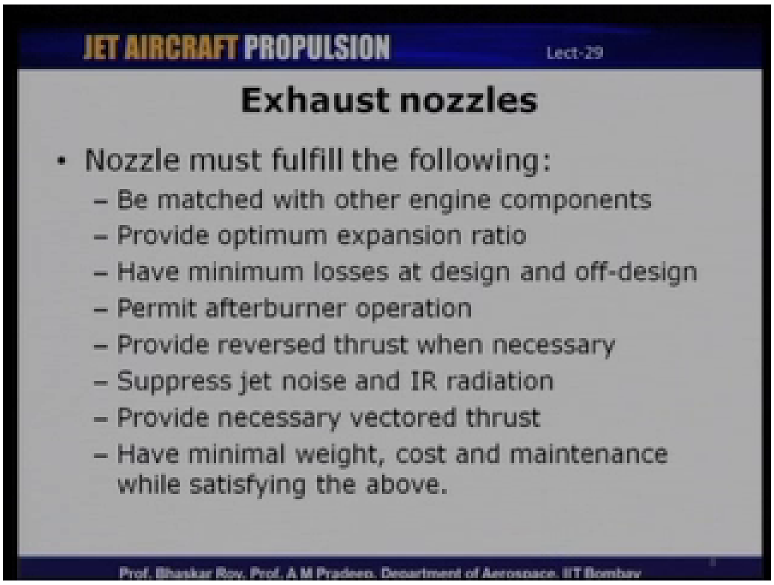


So, let us now look at in detail what are the functions or what are the conditions that a nozzle must satisfy, when it is operational. So, one of the functions when the nozzle is operational is that it should it should be matched with all the other engine components. So, you would very shortly be discussing about in some of the later lectures about matching of the compressor and the turbine and besides that, when an aircraft engine is operational, infact all the components should be matched. That is the mass flow coming in from the intake, it should be what that is required by the compressor and then that is what goes into combustion chamber and the turbine and finally through the nozzle.

So, all these components though they are though they can be analyzed separately at the distinct components by themselves, they are designed separately. When all of them are put in place, they all have to match and they have to operate as one single unit. So, nozzle also must be matched with other engine components and a nozzle should be such that it provides an optimum expansion ratio; so that, the thrust is optimal. Nozzle must have or must lead to minimal loses both the design as well as off-design conditions. Nozzle geometry must permit afterburner operation and this is where, the variable geometry comes in to picture that if if an engine really has an afterburner being used, the nozzle geometry must be variable; So that, it can permit the afterburner operation.

There are other functions which I have very shortly discussed and we will discuss in detail little later is that a nozzle must also provide reversed thrust when necessary; especially when an aircraft is landing. Reversed thrust would be required in most of the modern aircraft. The nozzle is also required to suppress jet noise as well as infrared radiation; which is IR radiation is suppression is true for military aircraft, where one would like to keep the aircraft as shielded as possible from enemy radar and therefore, IR signature should be kept minimal. So, that is possible by proper contouring of the nozzles. Then in combat aircraft, again one would meet a nozzle would be required to provide necessary vectored thrust.

So, as to carry out maneuvers which are really not possible using conventional control surfaces like ailerons or flaps. So, that is another function. Now besides all this, the designer must also ensure that the nozzle has minimal weight and complexities, while it is carrying out all these above functions. So, it means that though one had might have thought earlier that nozzle the function of nozzle is simply to generate thrust; that continuous to remain the primary objective of a nozzle. But besides that, nozzle also has to satisfy and generate or carryout several other functions like listed here. And some of these functions are restricted to military aircraft and some of them are common to both military as well as civil aircraft like reversed thrust is used in both of them; whereas, thrust vectoring is really used only in military combat aircraft.

So, in a modern day nozzle, when it operates under these different operating conditions, one would need to ensure that the type of nozzle that is used for the particular application is indeed optimum for that kind of an application. So, for example, convergent nozzles is the nozzle which one would use only in a subsonic aircraft with typical transport aircraft that one would have a convergent nozzle. In a super in a military aircraft especially with an afterburner on, a convergent nozzle would simply not suffice. One would need a convergent-divergent nozzle and ofcourse with a variable area facility. So, the nozzle must also be variable geometry, when it has to operate with an afterburner.

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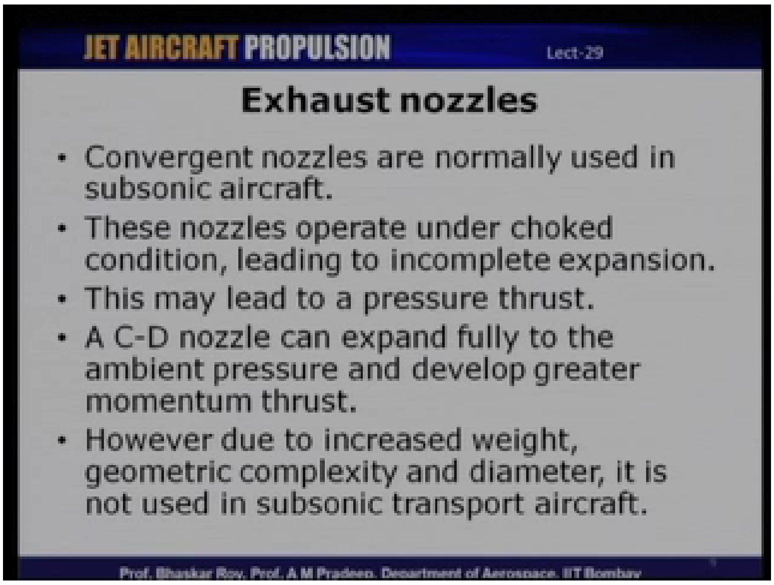


So, in convergent nozzle which is normally used in subsonic aircraft, normally these operates, these nozzles operate under choked condition. And so which means that the exit mach number is unity and in which case, we have an incomplete expansion taking place from the nozzle. Now, this can lead to the formation of a pressure thrust as we have seen earlier. That an incomplete expansion at the exit wherein there is a difference between the nozzle exit pressure, and the ambient pressure can lead to a pressure thrust term, which could either be positive or negative depending upon how the expansion is done. This is the limitation of a convergent nozzle. Now, if you use a convergent-divergent nozzle, then one can actually achieve a full expansion at the exit of the C-D nozzle.

And the C-D nozzles can also be designed to develop grater momentum thrust; which means that if one were to use a C-D nozzle in a subsonic aircraft, one can actually achieve a better performance theoretically. But using such a nozzle in in a normal civil aircraft means, it would lead to additional weight and complexity and also possibly also has larger diameter at the exit of the nozzle something which is not desired especially for a normal civil aircraft, which is the reason why, civil aircraft would simply use a convergent nozzle and not a C-D nozzle, which could really give you a slightly better performance if one or two or for that.

But other complexities and the weight and the cost as per as well as the overall diameter being larger really offsets the advantage of having a C-D nozzle over a convergent nozzle, which is why, a convergent nozzle is preferred for normally civil aircraft applications; whereas for military aircraft, it is not really a limitation there. One would need to optimize the engine for the best possible performance and therefore, one would definitely go for a C-D nozzle in a military aircraft, if the advantages are much more than that of a convergent nozzle. Now, as I mentioned there are fixed as well as variable types of geometries of nozzles and we have seen the limitations of fixed geometry nozzle. Let us now look at what are the different types of variable geometry nozzles which are in which are possible and which have been used in different aircraft.

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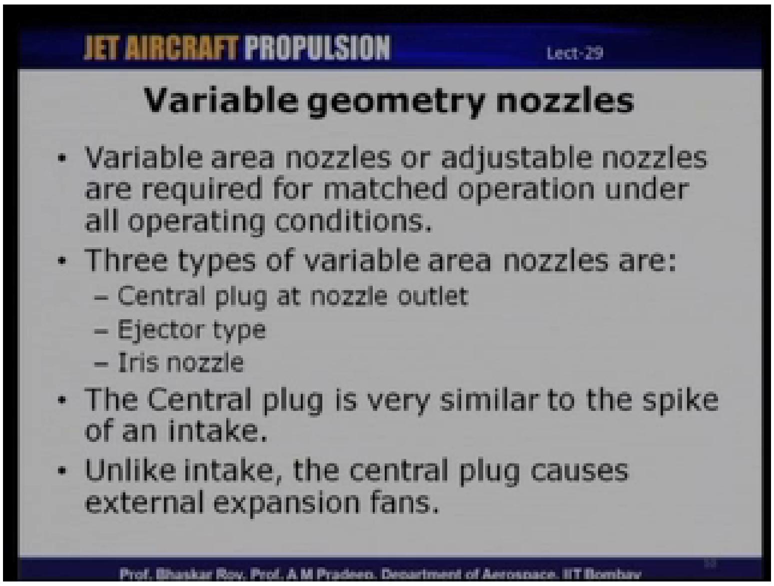


Now, variable area nozzles are adjustable nozzles as they are sometimes referred to or required for matched operation under all operating conditions. So, one of the functions of nozzle we have discussed is that it should be matched with rest of the components like the compressors and the turbine and so on. And if this has to satisfy under various operating conditions, then one would need to go for a variable area nozzle and there are different types of variable area nozzles which are available. One of the forms of variable area nozzle is known as the central plug nozzle; the other type is the ejector type or the third type is the iris type. So, these are three different types of nozzle geometries which are possible and which have been used in various aircraft over the airs.

Now, the central plug nozzle is very similar to the spike of an aircraft intake. We have just discussed the different types of intakes in the last lecture few lectures. Now, one of the types of intake supersonic intake was an intake with the spike. So, an ejector type of nozzle is very similar to that of the spike of an intake. In a spike intake, we have seen that this spike leads to the formation of oblique shocks and that is required for deceleration of the flow. Whereas, in an ejector type of configuration or in a central plug type of a configuration, instead of an oblique shock, we have expansion fans and expansion fans lead to the required expansion taking place through the ejector nozzle.

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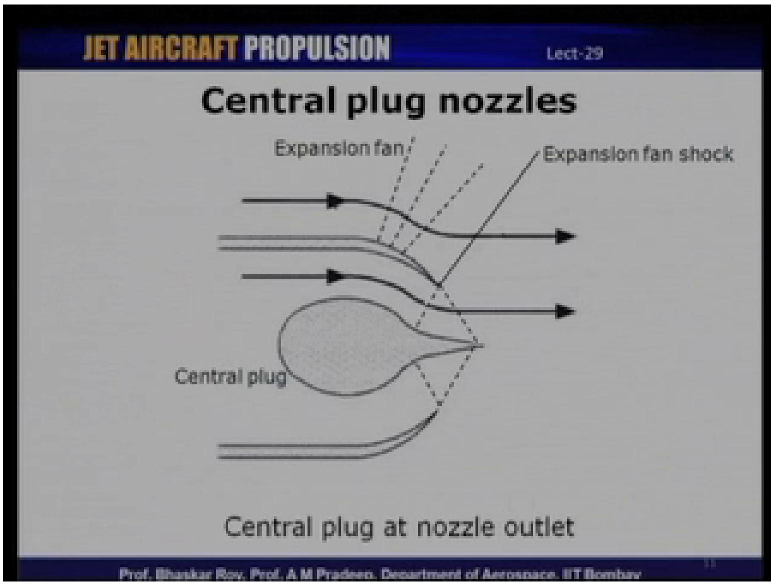


So, the figure that shown here is basically a schematic of a central plug type of a nozzle. We can say that what is shown at the center here is the central plug very similar to that of a spike of an intake, if the flow were coming on the other way from the other direction. So, and because of the varied geometry that you can see here, the flow gets deflected because of the presence of these fan expansion fan and these are the this is the expansion fan. And we have an expansion fan shock here at the lip of the nozzle or the exit of the nozzle. So, this central plug the position of the central plug can be adjusted axially leading to different areas at the exit and this is one of the ways of achieving a variable geometry. Same way we have discussed for an intake, the central spike or the ram can adjusted to achieve a variable intake area. The nozzle exit area can be changed or varied as we change the location of the central plug. So, this is one type of nozzle which has a central plug.

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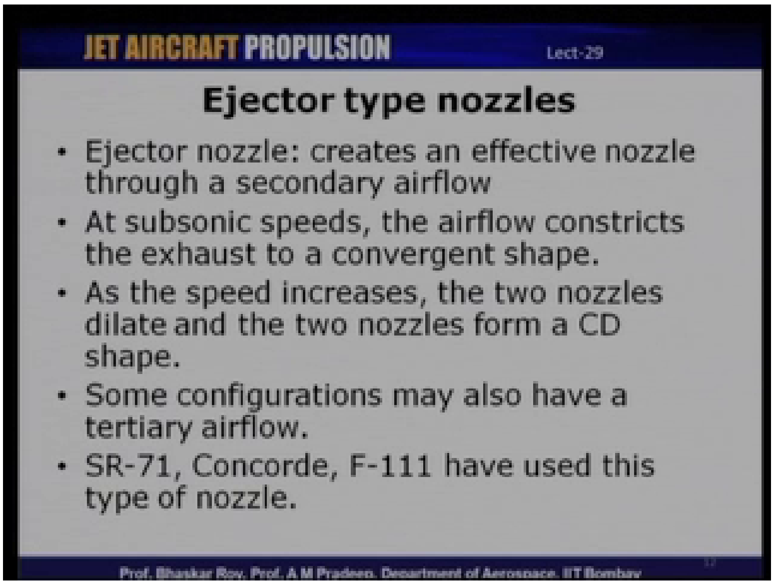


The other type which is slightly more complicated is the ejector nozzle, where it creates an effective nozzle through a secondary air flow and it can ofcourse be used in subsonic as well as supersonic speeds. And at subsonic speeds, the air flow constricts the exhaust to a convergent nozzle and as the speed increases, the nozzles will dilate and we get nozzle shape which is very similar to that of a C-D nozzle. And in certain configurations which are little more complicated, they may also have a tertiary air flow to achieve the same effect. Now, some of the aircraft which have actually supersonic aircraft, which have really used ejector nozzles are the SR-71 or the black bird a picture of which I had shown in one of the earlier classes, the Concorde which was the only transport aircraft which could fly at supersonic mach numbers and the F-111. So, these are different supersonic aircraft, which had ejector type of nozzle configuration.

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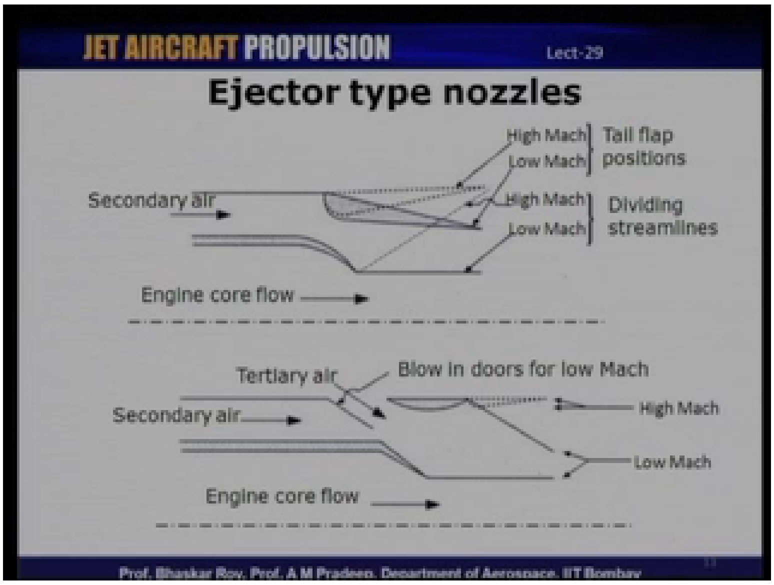


So, what does an ejector type nozzle look like? Now, these are the two types of ejector nozzles which have been used. One is a nozzle configuration which has just one secondary air; the second one has a tertiary air as well. So, in this configuration the first one that is shown here the secondary air is flowing through a duct or envelope, which is surrounding the engine core flow. The engine core flow is shown here and so depending upon the mach number at which it is operating; if it is operating at a low mach number as is shown here, then through the flap that is kept here is kept at a position which will result in the formation of a convergent nozzle. Which is what, one would really require for subsonic operation. As the aircraft approaches supersonic speeds, then the flap can be deflected achieving a converging and the diverging shape.

So, this is the flap location for high mach numbers or supersonic flows and therefore, the flap location gets changed or deflected. So, that one can achieve supersonic convergent-divergent nozzle leading to supersonic flows. So, the line shown here is a dividing stream line. the For low mach number flow, this basically would be the dividing stream line between the secondary air and the engine core flow. For high mach number flows, the dividing stream line also gets deflected substantially to achieve the required exit mach numbers. Now, the same effect is also possible using a tertiary air, where one can use additional air from or which is also known as a tertiary air and result in a similar effect, as what we had achieved using this is the secondary air flow.

So, here there is a secondary air flow as well as the tertiary air and tertiary air is basically used using or adjusted using what is known as a blow in door, which is used for lower mach numbers to achieve just a subsonic or a convergent nozzle for low mach numbers. And as the mach numbers increases, as we can see here the flap gets deflected and we have a convergent-divergent nozzle geometry, which can give us higher mach numbers or a supersonic flow at these mach numbers. So, these are two different types of configurations of ejector type nozzle. We have seen this the central spike or the central plug type nozzle; the other type is the ejector type and the third type is the iris nozzle.

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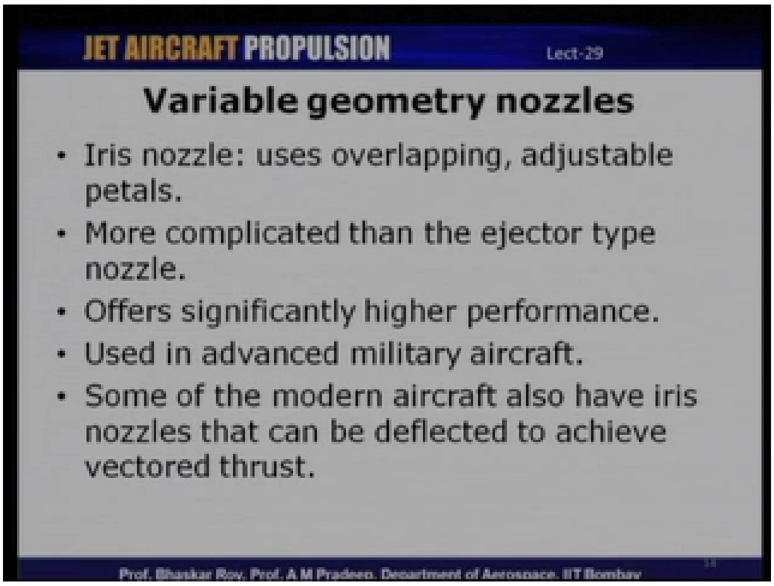


Iris nozzle basically uses overlapping and adjustable petals or flaps and these are ofcourse more complicated than the ejector or the other type of nozzles. But these offer substantially higher performance and therefore, they are normally used in advanced military aircraft nozzles and in some of the military aircraft, the iris nozzle itself can be deflected like one example that I am going to show now. The nozzle itself can be deflected to achieve the achieve vectored thrust. So, an iris nozzle basically consists of several flaps which are overlapping and if the area has to varied, the flaps can be opened up or closed. And therefore, that can give us variable area nozzle and the whole nozzle itself can be deflected to achieve vectored thrust. So, I have one example here of an iris petal type of a configuration of a nozzle.

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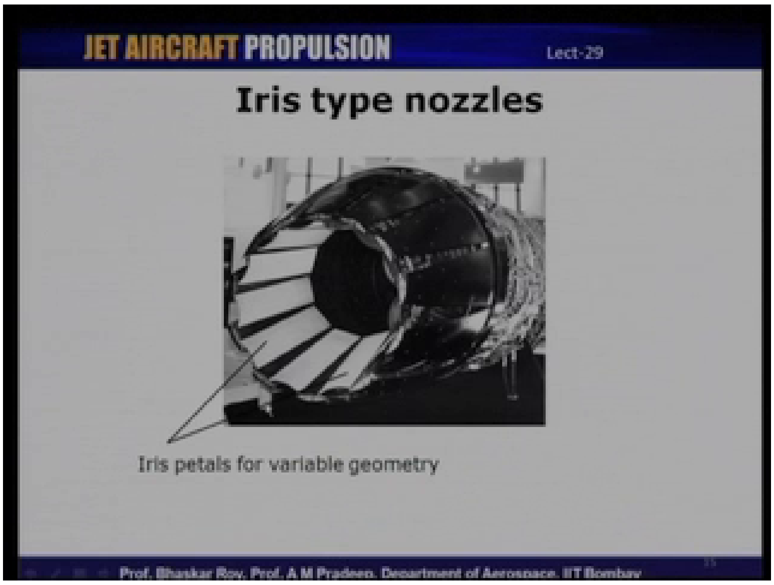


So, in this example that we have here there are different petals that are shown and these petals are basically overlapping and depending upon the operation, the the overlapping of the petals can be changed. Therefore, they can have variable area at the exit. So, in this example that you see here the various petals that are overlapping here; you can see the iris petals, which are that these are different petals which constitute the iris and these can be overlapped, depending upon their the the operation of the engine itself. So, this is the nozzle outlet or exit or outer surface and what you see here is the inner surface and this is a nozzle which can also be vectored or the the orientation of the nozzle can be changed to achieve a vectored thrust.

So, these petals the area can be varied as you can see here; if they are closer together, it will result in a lesser area exit area and if they are spread out, one gets a larger nozzle exit area specially required for operation with afterburner. So, these are three different types or configurations of nozzles which are possible; the the central plug type, the ejector type and the iris type. So, these are configurations which have been over the airs used in different types of aircraft for achieving the required functions from the nozzle. What we will discuss next are different other functions besides of course generating thrust, I have mentioned that there are nozzles have also other functions to perform and one of the other important functions is thrust vectoring.

Thrust vectoring is used in usually used in combat aircraft, in military aircraft to achieve maneuvers which are not really possible using conventional control surfaces. Thrust vectoring was originally developed as methods for achieving vertical or short take off and landing. But it was soon realized that one could also use this in normal military aircraft to achieve very substantial amounts of maneuvers, which are not really possible using the ailerons and flaps and so on. So, it was originally developed for achieving vertical take off or short take off and landing and slowly it has evolved into a method, which has now more or less become a standard for any modern day combat aircraft.

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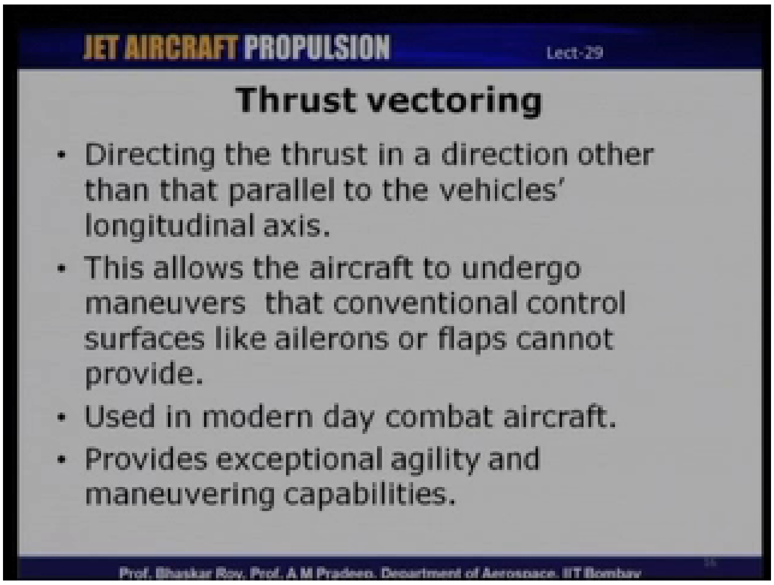


So, thrust vectoring basically involves directing the thrust in a direction which is something different from the vehicles longitudinal axis. And this allows the aircraft to undergo maneuvers, which cannot be carried out using ailerons or flaps and it is more or less used in most of the modern day combat aircraft. And it provides exceptional agility and maneuvering capabilities, which is one of the features. Well Important aspects of modern day combat aircraft that it should have very high levels of agility and maneuvering abilities and that can be achieved using a vectored thrust.

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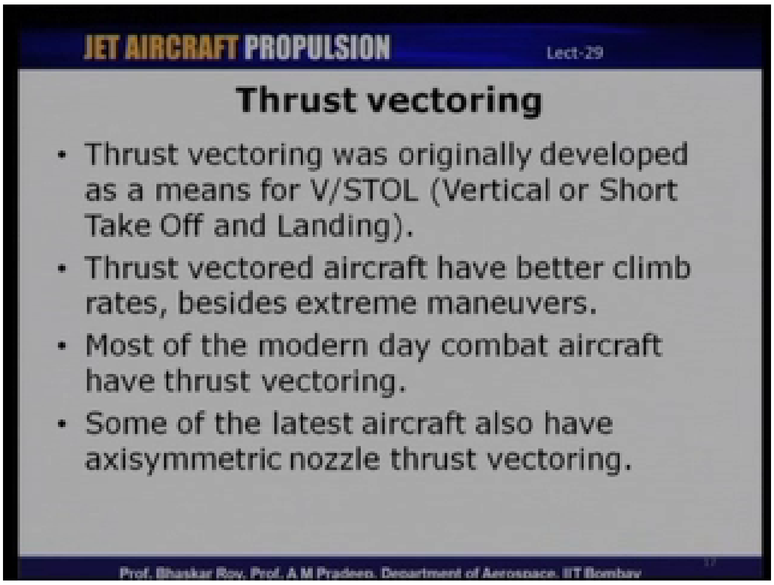


And as I mentioned, it was originally developed for achieving vertical or short take off and landing. And it is still used in some of the aircraft, which have vertical or short take off and landing like for example, the sea harrier which has more or less a vertical take off and landing, where the the the nozzles can be deflected in extreme directions to achieve a vertical or short take off and landing. Now, thrust vectored aircraft obviously will have better maneuvering capabilities; it can also have better climb rates. So, if one deflects the nozzle, one can achieve very high levels of climb rates which are not really possible using the conventional techniques. And some this thrust vectoring is a feature which is now used in most of the modern day combat aircraft.

And some of them also have axisymmetric nozzles, which can be vectored like the example I showed for the iris nozzle. It is an axisymmetric nozzle, but it can be vectored to achieve thrust in the desired direction. Now, thrust vectoring can be of two types. Now, you can achieve thrust vectoring by deflecting the nozzle. So, deflecting the nozzle can again be carried out in different ways. One of the ways is to deflect the nozzle using mechanical means through that is known as mechanical thrust vectoring; that is the nozzle is physically bend or twisted or deflected in different ways. The other way of achieving thrust vectoring is using fluidic thrust vectoring; that is using fluid injection in in some directions so as to achieve a vectored thrust.

In this case, ofcourse the nozzle is physically not deflected. But fluid is injected from the casing; So that, the effective flow direction or the jet exhaust direction can be deflected depending upon the direction of injection of the fluid itself. So, these are two types of thrust vectoring that are possible mechanical and fluidic thrust vectoring. Now, mechanical control basically will involve deflecting of the nozzle, which means that there has to be mechanisms by pneumatic or hydraulic means one can deflect the nozzle. And therefore achieve or therefore deflect the jet exhaust in the desired direction to achieve the required thrust or alter the direction of the thrust.

Now in fluidic thrust vectoring, one might either inject fluid or in some cases, one can also remove fluid from one of the surfaces or from the boundary layer of the nozzle to achieve a deflection in the thrust direction. So, most of the currently operating infact all of them currently operating thrust vectoring schemes are mechanical in nature. Fluidic thrust vectoring is still undergoing laboratory tress and modifications. And it would probably take a few more years before, fluidic thrust vectoring can really be used effectively for achieving a vectored thrust. Now, let us look at the different types of these thrust vectoring mechanisms.

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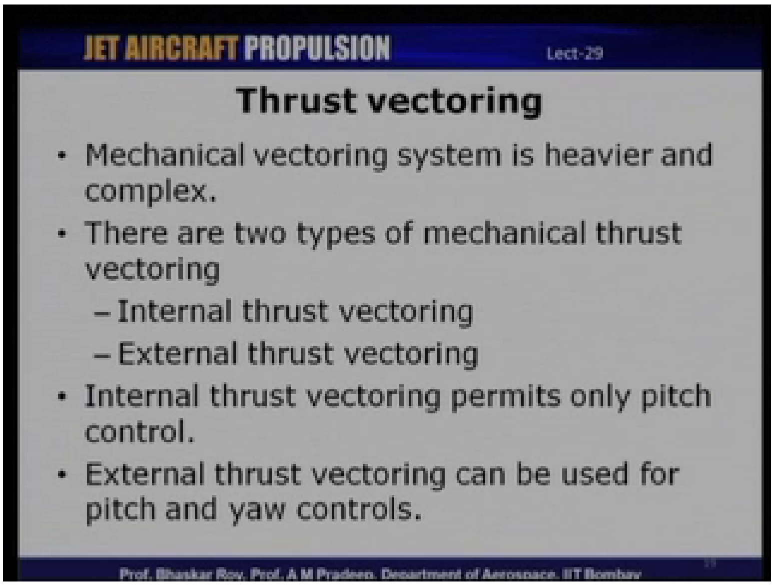


Now, mechanical thrust vectoring is probably more complicated or atleast heavier as compared to fluidic thrust vectoring. But they are simpler to implement and they have been demonstrated to be effective. There are two types of mechanical thrust vectoring that are possible; the internal thrust vectoring and external thrust vectoring. In internal thrust vectoring, it permits basically only pitch control; whereas, external thrust vectoring can be used for both pitch as well as yaw control and let us look at what these two types of thrust vectoring are.

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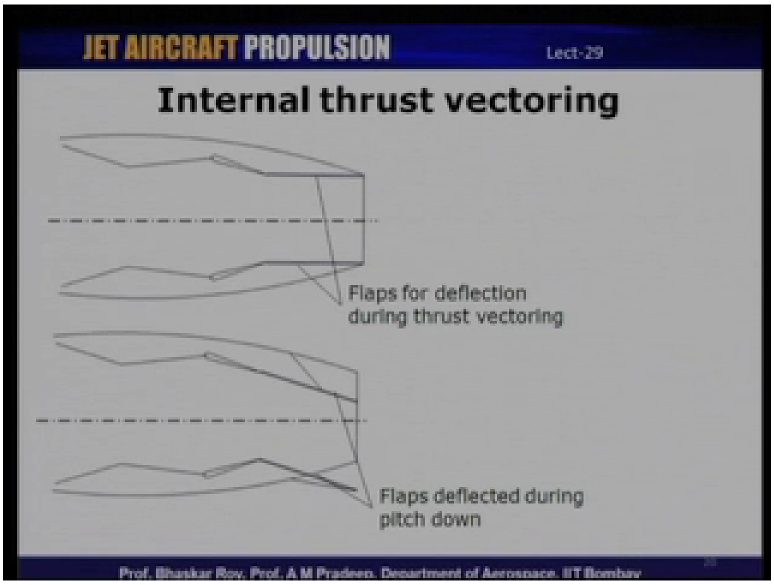


Now, in internal thrust vectoring, the jet exhaust flaps can be deflected in in some way or the other resulting in change of orientation of the jet exhaust and therefore a vectored thrust. So, these are the flaps of the exhaust nozzle, which can be deflected for vectoring the thrust. So, under pitch down for example if these flaps were to be deflected, so one gets a pitch control and if it what been deflected in the other way, the opposite direction of the pitch control is achieved. So, this is known as internal thrust vectoring; because it is the internal surfaces of the thrust of the nozzle, which are been deflected to achieve the thrust vectoring.

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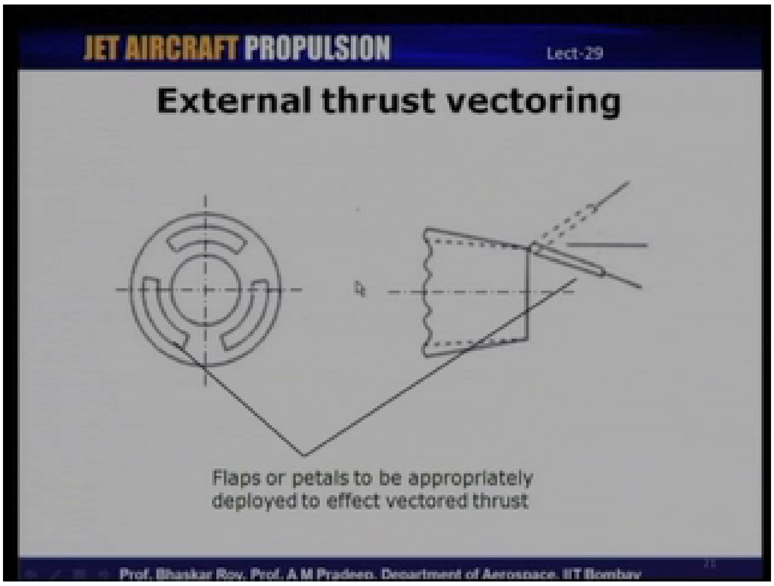


The other form is the external thrust vectoring wherein the flaps which are outside the nozzle which are deployed, when a thrust vectoring has to be achieved. For example, this flaps the three of them in this case; these flaps can be deployed. Either all of them or few of them can be deployed to achieve vectored thrust in desired direction. For example, if this the top flap is deployed, then it achieves an effect very similar to what is achieved in this case. Similarly, if the side flaps are deployed, then it gives us a yaw control, yaw vector and so on. So, in external thrust vectoring, it is also possible to achieve thrust vectoring not just in the pitch but also in your direction and besides this, ofcourse the whole nozzle itself can be vectored; in which case, one can get vectored thrust in any desired direction.

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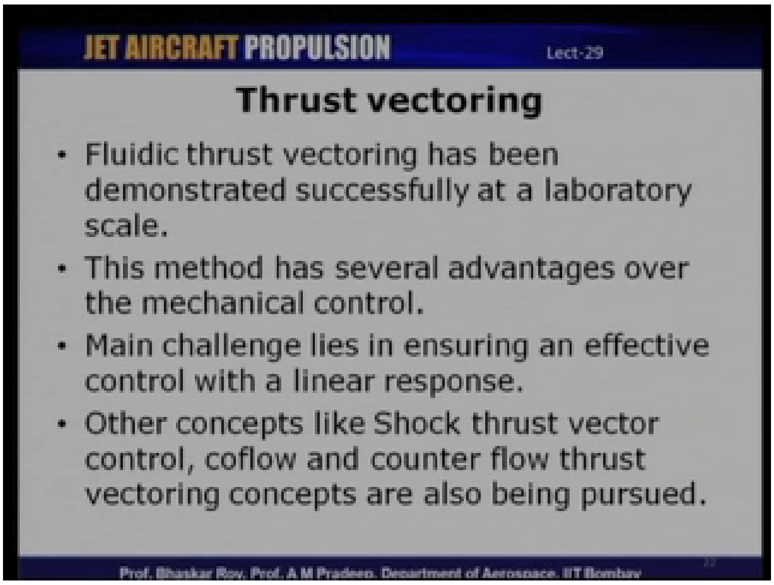


In fluidic thrust vectoring on the other hand, it involves injection of a fluid or section of a fluid. Though this has not really been used in an actual aircraft, it has been demonstrated very successfully in lab scale. And there are several advantages over over a mechanical thrust vectoring in the sense that here you do not need to have those complicated mechanisms and which obviously increases the weight of an aircraft and that is one major advantage with fluid thrust vectoring.

And that that is besides that, ofcourse the major disadvantage or challenge in using fluidic thrust vectoring is the fact that one would need to achieve an effective control, which is linear which is something which has not really been something not really been successfully demonstrated that the vector control has to be ha has to really have a linear response which is not which is something which is there in a mechanical control, which can be really controlled and programmed. Fluidic thrust vectoring can a times be and predictable in that sense. So, there are different types of achieving fluidic thrust vectoring like shock thrust vector control, Co-flow and counter flow control etcetera. These are basically being developed or demonstrated.

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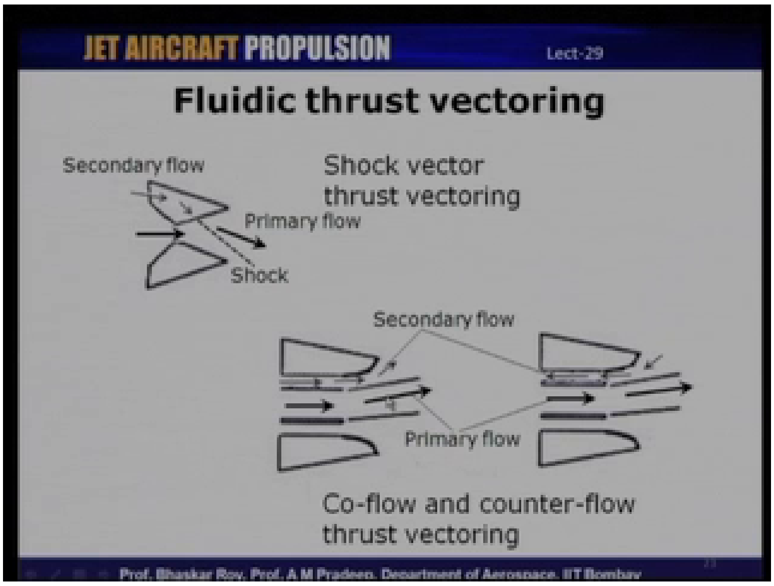


So, for example in shock vector control, injection of a secondary fluid from the nozzle one of the walls of the nozzle leads to formation of a shock, which will result in deflection of the primary flow. As we know, flow across a shock has to be deflected. So, if we inject a fluid from one of the walls, it leads to formation of a shock wave that leads to deflection of the primary flow and therefore thrust vectoring is possible in that case. The other concept is to use Co-flow or counter flow thrust vectoring using what are known as coanda surfaces.

Using the coanda effect that is if you inject a fluid a secondary fluid along the walls of the nozzle, it will tend to deflect the primary flow in towards that direction and that is basically because of the coanda effect. And this could be either in a Co-flow mode or in a counter flow mode that you could achieve the coanda effect and therefore thrust vectoring in that sense. But as you can see, both these require that the vectoring is reliable and it has a linear response to the flow rate which is used in these secondary flows. So, that is one of the major challenges in using thrust vectoring.

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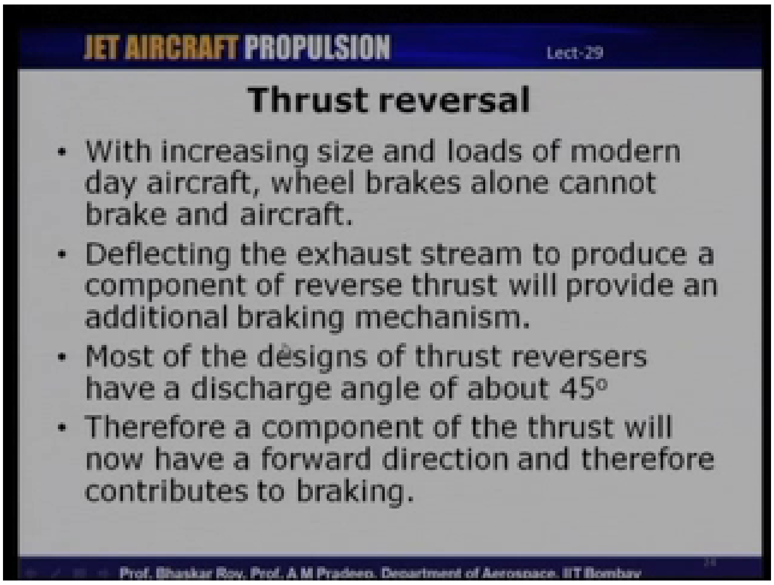


Now, the other major function of a nozzle is thrust reversal and thrust reversal as I mentioned is one of the ways of assisting the wheel brakes to decelerate and bring the aircraft to a stop in a shortest possible distance. So, with increasing size and weight of an aircraft, it is becoming more or less impossible to brake the aircraft just using the conventional wheel brakes. So, thrust vectoring involves deflecting the jet exhaust such that there is one component of the thrust, which is opposite to the direction of the thrust itself. That can lead to some amount of significant amount of in fact braking, which is a not really possible using conventional wheel brake.

So, modern day nozzles also need to have thrust reversal mechanism incorporated in their designs. So, thrust vectoring or thrust reversal basically involves deflecting the exhaust stream to produce a component of reverse thrust and normally these designs of thrust reversers have a discharge angle of about 45 degrees. Because it is not really possible to deflect the jet exhaust all the way up to 90 degrees; because that is going to create problems aerodynamic problems for the aircraft itself. And so there is a component of thrust which will have a forward direction and therefore, that will contribute towards braking.

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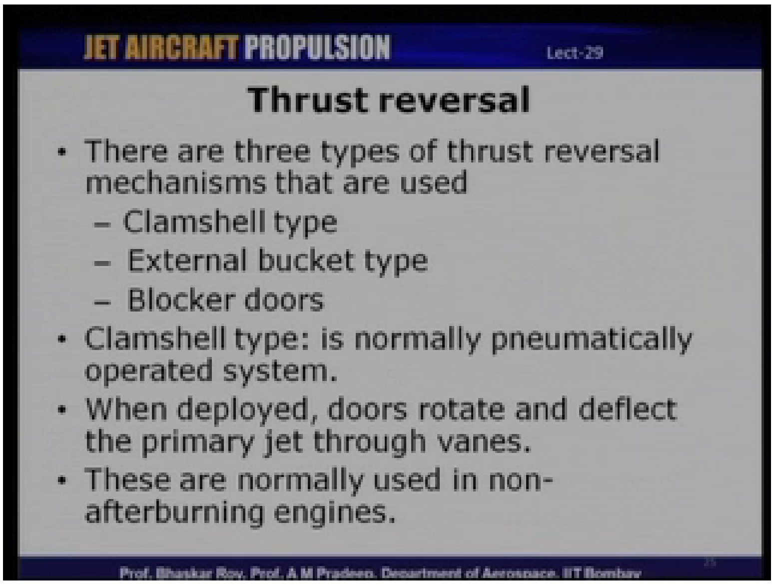


Now, there are again different types of thrust reversal mechanisms like the clamshell type, external bucket type and blocker types. Clamshell is normally pneumatically operated system, where in the doors which rotate and deflect the primary jet through vanes. These are used normally in not-afterburning type of engines.

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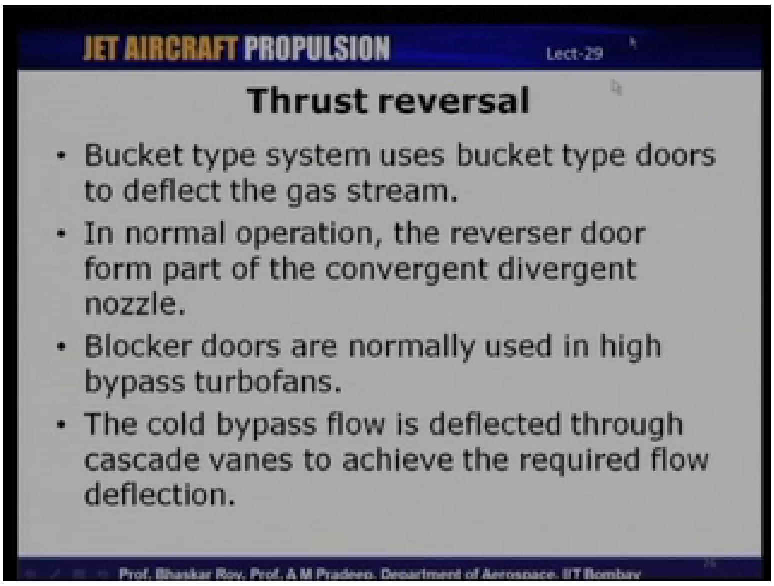


In the bucket type system, it uses bucket type of doors which deflect the gas streams and in a normal operation, this doors form part of the C-D nozzle itself. And in in a blocker type configuration, these are normally used in high bypass turbofans; where the cold bypass stream is deflected through cascade vanes to achieve the required flow direction.

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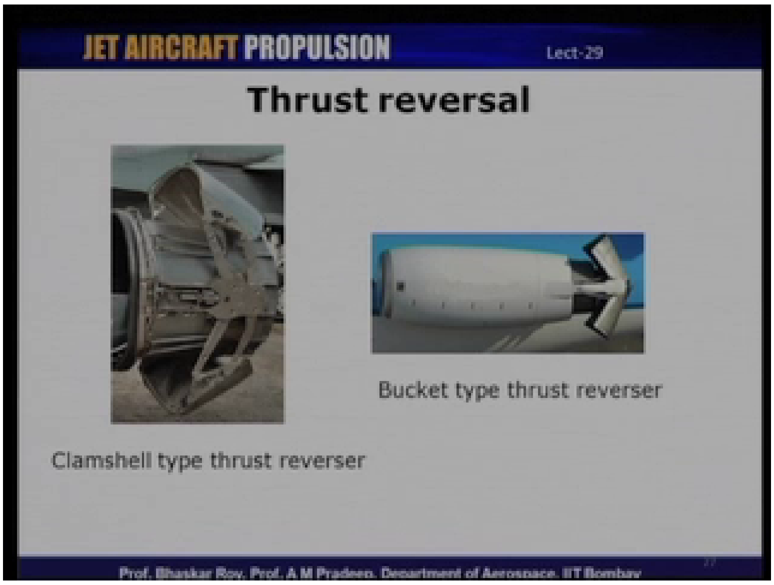


So, I have two examples here of the thrust reversal mechanisms used in aircraft. One is the clamshell type. So, these are the flaps which are deflected, when the nozzle has to give your reversal. So, the nozzle exhaust flow will get deflected through these directions; in this directions leading to one component of thrust which is in the reverse direction. This is a bucket type of thrust reversal, where the nozzle exhaust is deflected as you can say it is deflecting approximately at 45 degrees. And therefore, one there will be one component of reverse thrust leading to effective braking of this type of an aircraft.

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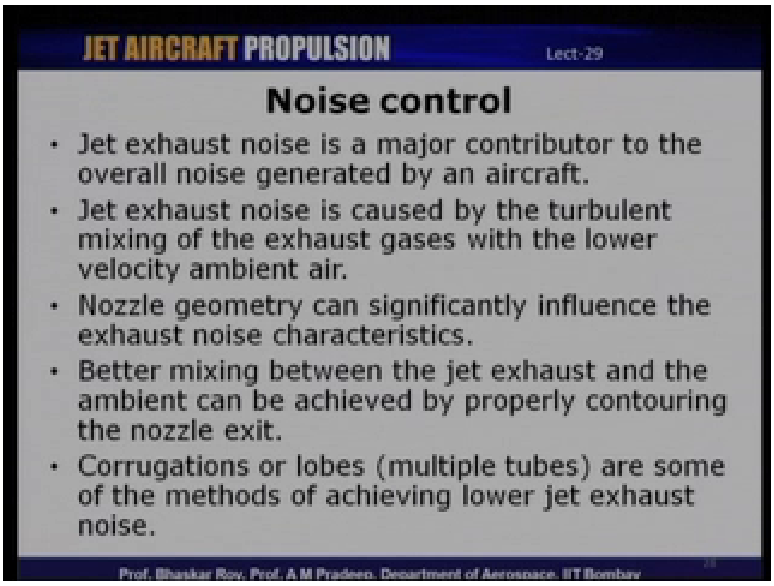


Now, the last function of an aircraft of a nozzle that we go in to discuss is noise control. I mentioned that jet noise is a major part or contributed to the overall noise. And so nozzle geometry can significantly affect or alter the noise characteristics. This can be achieved by properly contouring the jet exhaust nozzles with corrugations or lobes and so on. So, that the jet exhaust mixes effectively with the cold ambient flow. And so better mixing between the jet exhaust and the ambient can substantially reduce noise.

So, there are certain types of nozzle geometries which have been tested using certain serrations or corrugations on the nozzle exit contour and that has shown to show substantial noise reduction. But ofcourse there are other challenges like it also results in some losses to the nozzle efficiency. And that is something which has to be looked in to before these are actually used effectively in almost all the aircraft would ofcourse noise reduction will continue to be one of the major challenges of engine manufacturers.

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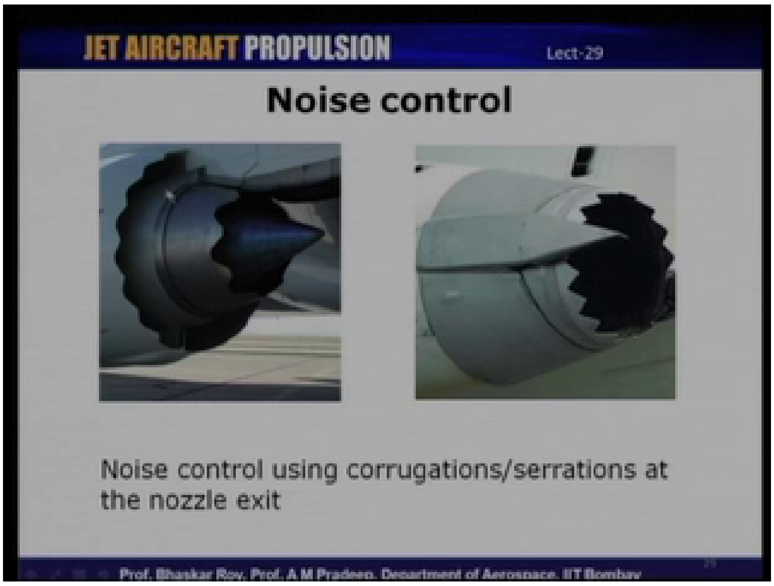


So, I have two examples here; where some of these concepts have been tested and you can see this is the bypass duct of the turbofan. This is the core duct and there are serrations which have been provided for the nozzle exit and that is one of the ways of reducing noise. And this is for convergent nozzle in a turbojet, where there are serrations as we can see. Both of them are primarily meant to a control or reduce noise. Now, so let us now wind up this lecture with a quick discussion on what we have talked about in this lecture. So, in this lecture we have been discussing about nozzles.

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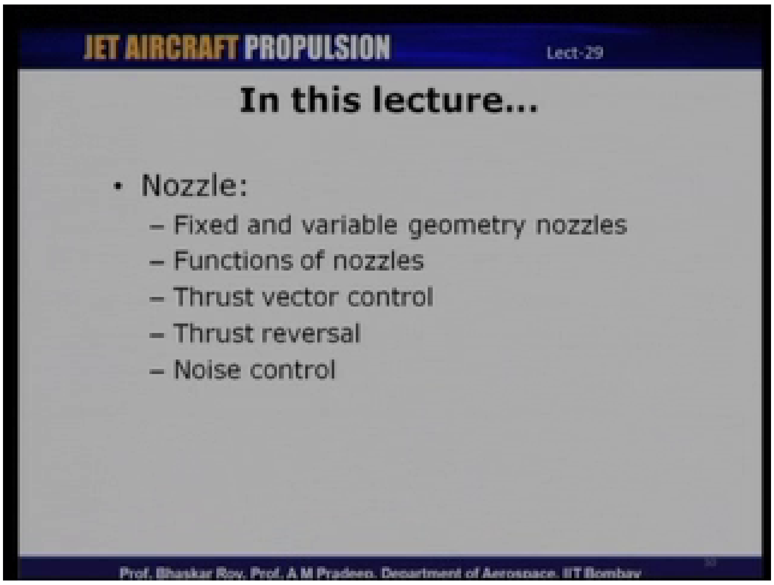


We started our discussion on two different types of nozzles; the fixed and variable geometry nozzles. We then discussed about functions of nozzles. Then, three other important functions of nozzles being thrust vector control, thrust reversal and noise control. So, these are functions of any modern day nozzle.

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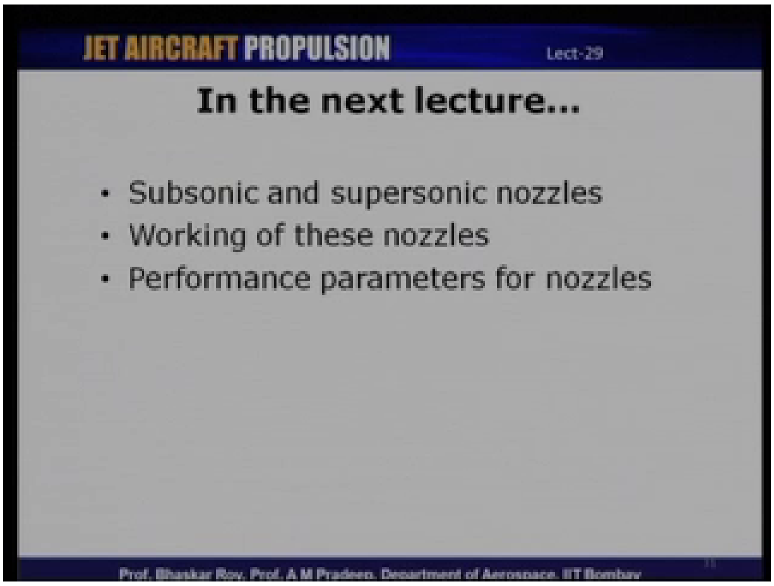


We will continue our discussion in the next lecture as well on nozzles, where we shall basically talk about subsonic and supersonic nozzles, working of these nozzles and basically on how these nozzles work. You will also come up with certain performance parameters for assessing the performance of different types of nozzles. So, some of these topics we shall take up for discussion during the next lecture.