Jet Aircraft Propulsion

Prof. Bhaskar Roy
Prof. A.M. Pradeep
Department of Aerospace Engineering
Indian Institute of Technology, Bombay

Lecture No. # 28
Subsonic, Transonic, Supersonic Intake Designs

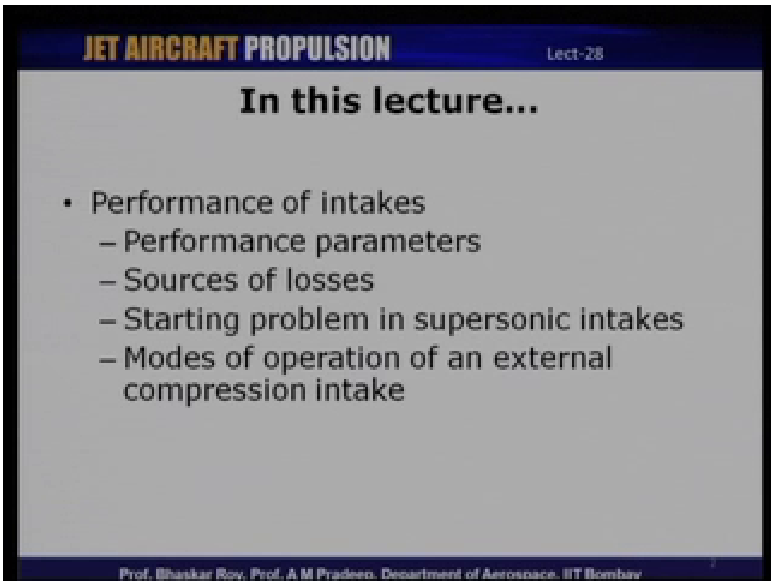
Hello and welcome to lecture number 28 of this lecture series on jet aircraft propulsion. We have been talking about some of the aspects related to one of the components of a jet engine that is the air intake. We have of course, already covered discussion on other components like compressors, combustion chambers and turbines, and I mentioned in the last class that intakes also form a very important component of the engine. Even though intakes are not really manufactured or fabricated by the engine manufactured it is usually manufactured by the air frame manufacturer of course, in consultation with the engine manufacturer.

So, in the air intake forms part of the engine main it is installed in an aircraft and not as a standalone unit, and we also discussed about in the last class about what are the functions of air intake, what are the different types of air intakes which are used? Basically there are two distinct classes of air intakes, one which is used purely for subsonic flows and the other class of intake which are use for supersonic flows. And we also seen that their lots of difference is between these types of intakes, because of the fact that both these intakes have to operate in different modes or in different regimes of operation.

One of them has to operate in supersonic mode in which case the mode of compression is quite different from what it occurs in subsonic flows, and that makes whole lot of difference between the geometric constructions of a subsonic intake as compared to a supersonic intake. We have also seen that in general subsonic intakes are simpler in terms of the design as compare to supersonic intakes. And today will discuss little more on intakes will primarily be discussing about what are the sources of losses or how you can account for performance of these intakes, and what are the performance parameters that can be associated with an intake.

We will also be discussing in little bit details about some of the issues related to supersonic intakes like what is known starting problem, and what are the critical modes of operation of an external compression intake. So, in today's lecture what we are going to discuss about are the following. We will first talk about performance parameters, we will see what the different parameters are that can be used to judge the performance of air intakes.

(Refer Slide Time: 02:54)



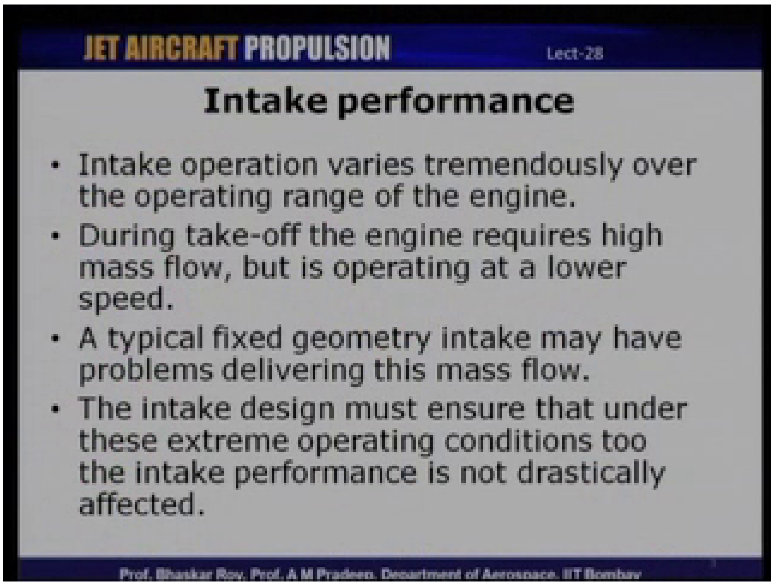
We will then look at where the losses are originating or what are the sources of these losses. We will also be talking about starting problem associated with supersonic intakes will spend some time on what is mean by starting problem. And then subsequently will talk about what are the modes of operation of an external compression intake. So, these are some of the topics that we shall be discussing in today's lecture and I think in the last class I also mentioned that an intake as to operate over a verity of operating modes that is as in aircraft takes off it is operating at a very low speed.

At the same time aircraft requires the maximum thrust during takeoff which means that the mass flow requirement during takeoff is quite high and after the aircraft as taken off and it as claim to the required altitude. Then it is begin in cruise that is when the aircraft does not requires maximum thrust at the same time it would have attained its maximum speed. So, the mass flow requirements in those these two cases are quite different and also the speeds of operation are quite different and if it is a fixed geometry intake like what is used in most of the transport civil aircraft, the subsonic type of aircraft then which have fixed geometry intakes.

Then unless the intake is very carefully design under these extreme operating conditions there could be lot of issues with regard to operation and performance of these intakes itself. So it is necessary that an intake manufacture or designer keeps these things in mind and in sense that the in designer obviously, would know the range of operation or the flight regime of a particular aircraft. He has to keep in mind the fact that under different operating conditions the engine requirements acquired different and it is the intake, which is going to supply the required mass flow rate not just the quantity, but also of good quality in terms of a uniform flow into the engine because that is very essentially for proper operation stable operation of the engine.

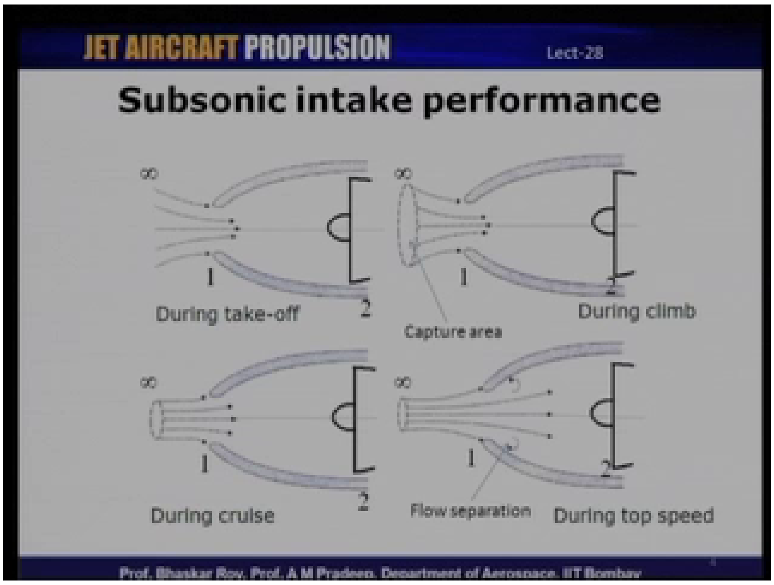
So, an intake having to operate under these circumstances will have to keep in mind the designer will have to keep in mind the fact that there could be conflicting the requirements on what is the operating mode during takeoff as compare to what happens during cruise .

(Refer Slide Time: 05:35)



So, in a fixed geometry intake there is this problem that you cannot change the geometry, but what you do if you cannot change the geometry. So, it as to be a trade of between the operating conditions. So, because of the fact that intake operation varies tremendously over operating range for example, during takeoff the engine requires a very high mass flow, but it is operating at a low speed and so in fixed geometry intake it is lightly to have issues with delivering this mass flow during takeoff and it is the duty of the intake to supply the required mass flow without affecting the engine performance.

(Refer Slide Time: 06:12)



Let us take one quick look at an example where we see what are what really happens as the operating conditions change for a fixed geometry subsonic intake. So, here we have a fixed geometry subsonic intake. So, this is how a typical intake would look like for let say a transport aircraft let say going 7, 4, 7, 7, 7, 7, 7, so on. So, all this aircraft are typical subsonic transport aircraft they all have intakes which look like this and this is the compressor phase of the engine this is the hub of the engine. So, during takeoff as I mention the engine is operating at low speed and it requires the high mass flow, which means that the stream lines the engine would try to capture stream lines from the free stream from infinity.

So, this is our free stream which is been represented as infinity. So, during takeoff the capture area can be extremely high its which is I have not really shown the capture area here capture area refers to the area of this stream tube which actually enters into the engine in when the engine is just beginning when the aircraft is just beginning to takeoff just when its speed is very low thrust requirement is very high capture area can be extremely high. Now, once the engine as taken off and during claim the capture area is still high.

In fact, it is larger than the intake entry area, but it is still definable you can still associates some area with this and that is why we have I shown a distinct area for this stream tube and that this is the capture area under this condition which is during claim during cruise. On the other hand you can see that the capture area as reduces substantially. It is usually often area which is lower than the intake entry area as you can see here, which means that they will be some amount of deceleration or diffusion taking place even before the flow enters the intake because this is subsonic flow.

And if the engine is accelerating beyond its cruise Mach number then there are possibilities that the capture area becomes even smaller in which case there is a possibility that because it is a fixed geometry intake the adhesive pressure gradient here would be quite high for the flow to sustain itself and there could be there could be an occurrence of flow separation on these valves which obviously, would lead to poor performance of the engine and this could happen if it is operating at Mach numbers flight speeds slightly more than the design Mach number that is during cruise.

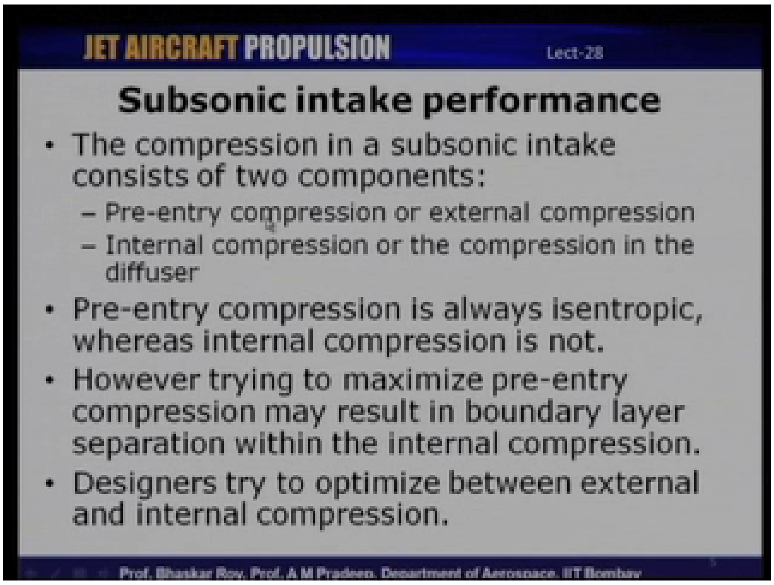
So, this is just an example of different modes of operation of a typical subsonic fixed geometry intake and this is something which all intakes which are operating in this regime will have to undergo that during takeoff as certain there are certain requirements for takeoff there certain requirements for climb cruise and so on. And because the geometry is fixed the designer as to ensure by careful optimization that the engine performance is not compromised under any of these operating conditions which mean that there could be instances where the intake is not operating is not designed for an optimal operation, which is probably during takeoff and climb.

But during cruise is when the intake engine is or the aircraft is going to operate for the longest duration. So, the intake is usually design to operate most efficiently when the aircraft is cruising whereas during takeoff and climb because those the intenseness of the takeoff or the time period of takeoff climb is much smaller. The engine designer the intake designer as to make sure that the engine the intake operates efficiently though not optimally for that particular operating condition. Now for a typical subsonic intake like what we have been discussing now.

There are two modes or two parts of deceleration or compression taking place. One part of the compression is just before the intake that is even if even before the flow enters the intake there in some operating conditions there could be deceleration and the other part of deceleration is of course, within the diffuser or the intake itself. So, there are there is an external compression which is on account of the pre entry compression as it is called and the other component of this compression is within the diffuser itself. So, these two constituents put together result in the overall diffusion or pressurize that occurs within as a result of the diffuser.

But the pre entry compression of course, is limited to only certain modes evaporation like during cruise as we have just seen during takeoff. In fact, there could be an acceleration pre entry acceleration taking place. So, there is not that does not really contribute towards the overall pressurized taking place in the intake and so under these two operating conditions. We will now see what really happens within the intake and how we can evaluate what is really happening in terms of pressurized under these two circumstances that is pre entry compression and the internal compression.

(Refer Slide Time: 11:49)



So, compression in subsonic intake consist of two components as I said one is the pre entry compression or the external compression and second part of the compression is internal compression or compression within the diffuser and pre entry compression is that part of the compression, which occurs just before the intake entry itself and because there are no solid surfaces bounding the pre entry compression pre entry compression is always Isentropic. On the other hand internal compression is occurring within the diffuser surface itself and therefore, internal compression is not always in fact, it is never isentropic.

It just the pre entry part of compression which is Isentropic which means that it is free from losses. Isentropic compression is always good because it is free from losses. So, one might wonder then why do you. In fact, have any internal compression at all why cannot we have the entire compression taking place outside the diffuser itself, which means that there no losses in the diffuser we have hundred percent efficiency for diffuser. Ideally as one would like to do that, but then the very fact that pre entry compression is a result of the presence of the intake itself that is if you do not have an intake there is no more pre entry compression.

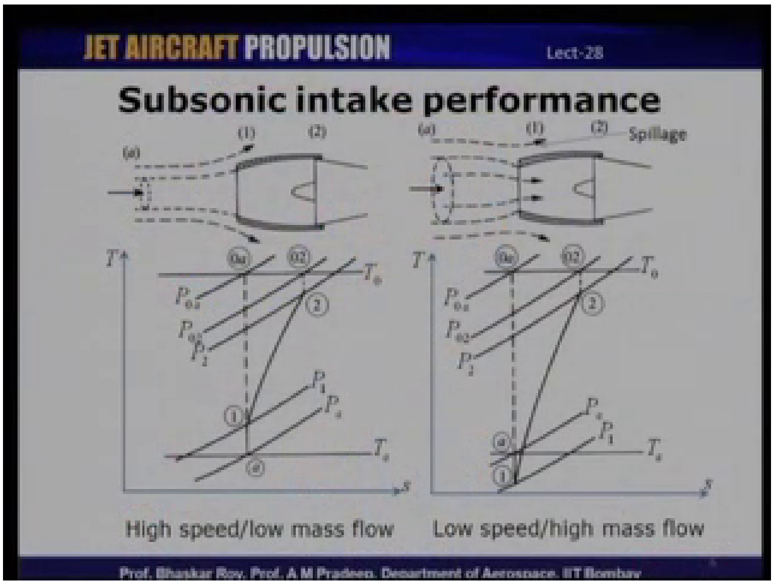
So, intake the diffuser itself is the result or the cause of pre entry compression and one could definitely try to maximize the fraction of pre entry compression to the overall compression which is what designers may try to do. But in doing so what happens is that pre entry compression as you have seen is very sensitive to the operating condition. That is if the aircraft is taking of or if it is climbing there is no pre entry compression. On the other hand if it is cruising obviously, there is pre entry compression.

So, because of the fact that pre entry compression is very sensitive to the operating conditions designers not would not want to always try to maximize pre entry compression and see what they try to do is to get a trade of between the fraction of pre entry compression to the compression taking place within the diffuser to ensure that there is a proper balance between these two components of diffusion and the other possibility is that pre entry compression might sometimes trying to maximize pre entry compression might sometimes lead to occurrence of flow separation within the diffuser.

As you have seen in the example I was discussing if the aircraft is let say operating at the Mach number, which is slightly higher than the cruise or Mach number then because of the pre entry compression there could be chances of flow separation within the diffuser surface which is obviously, not a good thing for the engine. So, we will now discuss about two different two extreme cases. One corresponding to takeoff where the engine requires high mass flow and the aircraft is operating at a low speed.

The other extreme is of course during cruise when it requires lower thrust or lower mass flow, but it is operating at high speed. So, let us look at thermodynamically what happens under both these operating conditions and we will try to appreciate the fact that pre entry compression does play a significant role in the overall compression process.

(Refer Slide Time: 15:20)



So, what I have shown here are two different cases. One is corresponding to high speed low mass flow which been takeoff which means a cruise high speed low mass flow corresponds to cruise the other extreme is takeoff which is low speed and high mass flow. Let us look at the cruise condition first. Now during cruise the engine requires lower mass flow because the thrust requirements are lower at the same time it is operating at a high speed. Now because it is operating at a high speed the engine as I said is usually design for this kind of an operating condition where you would prefer to have some amount of pre entry compression. You can see this is capture area capture area is much smaller than the intake entry area.

This is the intake entry area this is the capture area. Capture area is lower than this which means that because it is a subsonic flow increase in area would lead to diffusion there is a diffusion taking place from free stream all the way to the intake entry. So, this corresponds to pre entry compression or pre entry diffusion and once the flow enters the diffusion geometry because of the very fact that they this is a diffusing geometry in a subsonic flow there is compression taking place internally also and that is the internal compression. Let us look at this process on temperature entropy diagram T S diagram.

So, initially the air was at an ambient temperature of T a and a pressure of Pa and so this part of compression which is from station a to 1 is the pre entry compression and that is why you can see that it is a straight line which means that it is Isentropic and I had already mention that pre entry compression is always Isentropic. Because there no losses of friction there no sources of loss occurring in any of this part right from in a to 1. So, this is Isentropic compression from 1 to 2 is diffusion internal diffusion which is non Isentropic. You can see it is non isentropic diffusion from 1 to 2.

Now, if the whole process verse to Isentropic then you would have got stagnation pressure of P 0 a and because of the fact that there is a certain pressure loss taking place within the internal surface of the diffuser, the pressure that you ultimately get at station 2 is P 0 2 which is less than P 0 a. P 0 a corresponds to the Isentropic pressure stagnation pressure that you would have got if there were no losses internally. P 0 2 is the actual pressure that you get stagnation pressure that you get because of the fact there are losses frictional losses occurring internally.

So, there is difference between P 0 a and P 0 2 and so will subsequently define an efficiency which is based on this fact. So, and you can say what is to be kept in mind is that there is no change in stagnation temperature stagnation temperature corresponding to station 2 and station a are the same. There is no changing stagnation temperature because stagnation temperature change can occur only if there is heat transfer to the system or from the system. In this case if you assume that these surfaces are adiabatic the flow is adiabatic there is no heat transfer taking place. There will not be any change in stagnation temperature although there is still a change in stagnation pressure P 0 2 will be less than P 0 a.

Now let us look at the other extreme operation that is during takeoff it is low speed high mass flow and I mentioned that this in intake intakes are usually design to for operating efficiently during cruise which means that if it is fixed geometry intake. Because the mass flow requirement is very high the intake area is fixed and the speed is low it means that we would the capture area up stream as to be very large. Because if the engine as to if the intake as to supply that much mass flow rate capture area as to be large because it is this mass flow which will ultimately going to the engine at this speed.

Now, during cruise you can see that the speed is very high and therefore, when a smaller capture area would supplies in this case that would not because the speed is low, you need larger capture area to deliver the required mass flow rate and the problem with both of course, both these operation is that there is some amount of what is known as spillage. We will discuss spillage in little detail later on spillage corresponds to that those stream lines which escape and move over the surface of the intake that is known as spillage. If you look at T S diagram for this process the process begins at station a and you can see this area is larger than the intake entry area.

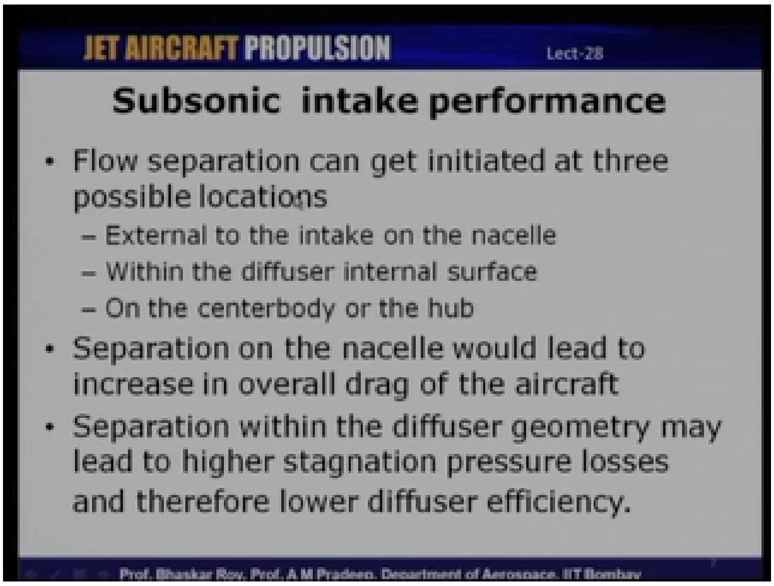
And because this area is larger there is an acceleration taking place here and there is an acceleration much which is Isentropic. Because there are no losses occurring because there is acceleration there is drop in static pressure. So, this is P a which corresponds to the ambient static pressure P 1 corresponds to the static pressure at station 1 which is the intake entry. So, there is drop in static pressure from station a to station 1 and then diffusion takes place from 1 to 2. So, you can see that in this case of course, that again at the exit of the diffuser the stagnation pressure is P 0 2 which is less than P 0 a T naught corresponds to this stagnation temperature there is no change in stagnation temperature.

Here you can see that the internal compression the fraction of internal compression is larger than what happens here because here P 1 was greater than P a in this case P 1 is lower and P a there is a larger pressure gradient which means that if this area if they decide engine or the intake was not design efficiently under certain cases there could be local flow separation taking place because of the very high pressure gradient that is important here. So, in these are two distinct modes of operation of a subsonic fixed geometry intake and we have seen that under two extreme conditions the intake operates very differently which is something that one would have expected and because of the fact that the intake is operating in different modes and the geometry is fixed under half design conditions.

You can see that the intake operation is quite different somewhat it is at the design condition at the design condition the designer would have tried to have some component of pre entry compression as well. So, that pre entry compression which is Isentropic and loss free also leads to some amount of overall pressurized. Whereas a drop design conditions like during takeoff for example, pre entry compression does not exist and in fact there is a an acceleration taking place pre entry and therefore, that increases the pressurized that as to take place internally and that is by the optimization now the intake comes into picture that they designers needs to make sure that even though the pressurized that internal compression as to take give does not lead to substantial pressure gradients which might lead to flow separation.

So, which brings us to the fact that there are certain operating conditions under which intake might operate sub optimally and there could be flow problems associated with operation of such an intake. So, let us take look at what are the possible regions of flow problems which typical fixed geometry subsonic in take might encounter.

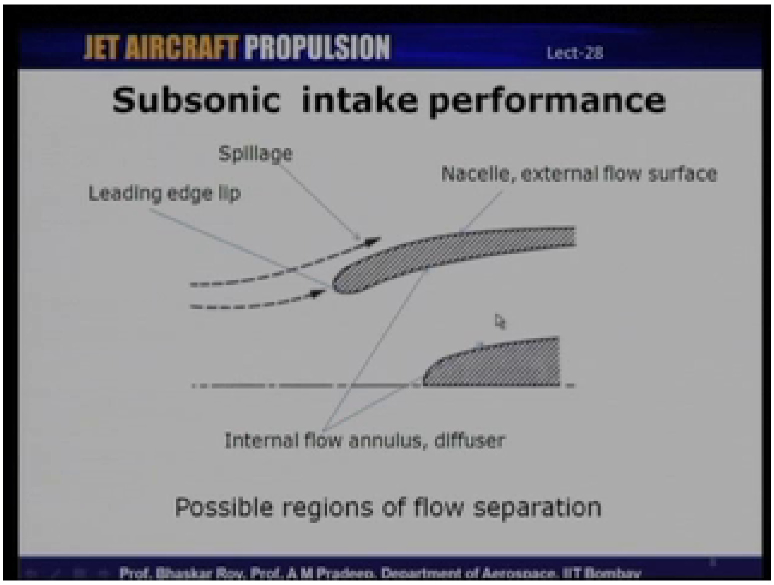
(Refer Slide Time: 23:50)



So, there are three possible locations for flow separation in typical subsonic fixed geometry intake. One is of course, external to the intake that is on the nacelle the other are the other two locations are within the internal part of the diffuser itself. One is within the internal diffuser internal surface; other possible location is on the centre body or the hub. Now, if you have flow separation on the nacelle which is possible a reason result of spillage, which occurs on the intake.

Spillage mightily to flow separation on the nacelle under certain conditions this can increase the overall drag of the aircraft and separation within the diffuser geometry obviously, may lead to higher stagnation pressure loss and therefore, lower diffuser efficiency we going to define diffuser efficiency shortly. So, pressure flow separation can lead to higher pressure losses which mean lower diffuser efficiency.

(Refer Slide Time: 24:53)



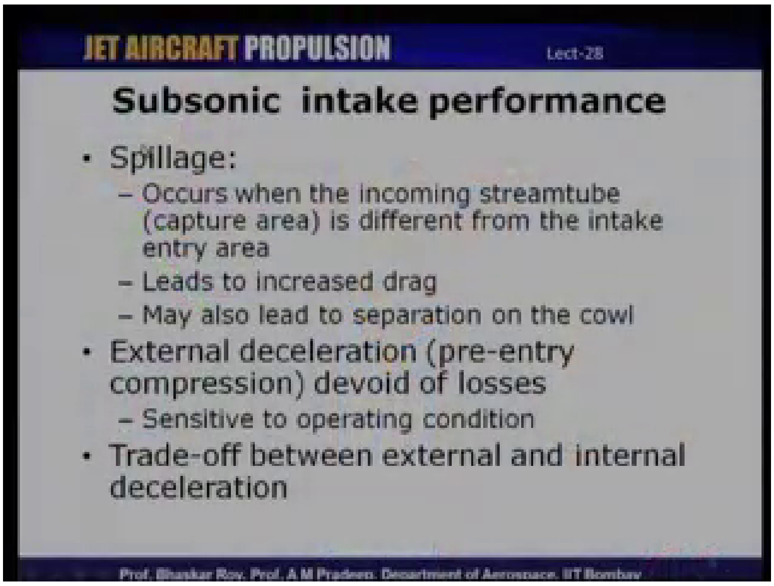
So, these are this just an illustration of where these flow problems might occur. This is the leading edge of the intake which is the lip of the cowl and this is the external surface of the nacelle and one of the sources of or possible locations of flow separation is on the external surface, which might occur if there is large difference between the capture area and the intake entry area under which conditions there could be substantial amount of spillage and spillage under extreme operating conditions might lead to flow separation from the external surface which obviously, increases the overall drag of the aircraft.

The other two locations of one are on the internal surface I mentioned that during takeoff. For example, the capture area is very high very large and there is a pre entry acceleration taking place leading to drop and static pressure at the intake entry, which means that there is the amount of pressurized that the internal surface of the diffuser has to take place is much larger, which might in some cases leads to flow separation from the internal surface and under certain conditions flow might separate from the centre body or the hub of the engine aspect.

In fact, both these sources of separation which are internal to the diffuser affects the diffuser performance in terms of its efficiency and pressure stagnation pressure ratio separation external to the surface does not really affect the diffuser performance, but it affects the aircraft performance as whole with because it increases the drag. So, these are possible locations of flow separation which might affect the performance of the intake two of them obviously, affect intake directly they are external separation on the nacelle affects the aircraft performance as whole.

Then we have seen that the some stream lines which do not form part of the capture stream tube or the capture area and under some operating conditions these stream lines escape and move over the surface of the nacelle. This these stream lines are basically referred on the mass flow associated with this is refer to as spillage. Now, spillage is under certain operating conditions under half design conditions may lead to increased external losses that is external drag.

(Refer Slide Time: 27:35)



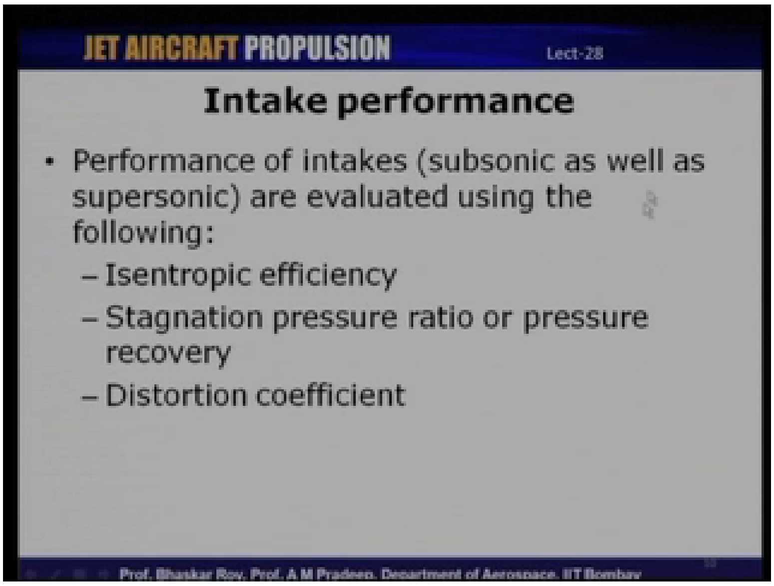
So, spillage is something which occurs under two conditions. One is if the capture area is larger than the intake entry area or even if the capture area is smaller than the intake entry area, which means that spillage will occur will not occur only if the capture area is equal to the intake entry area. So, spillage always occurs when the incoming stream tube or the capture area is different from that of the intake entry area presence of spillage will lead to increase drag and under certain conditions may also lead to flow separation on the cowl or on the nacelle.

Now a designer would like to maximize external deceleration or pre entry compression because it is divide of any losses and but the problem with this is that one first problem is that it is very sensitive to the operating condition and the other issue is that external deceleration may also caused the occurrence of spillage, which increases the overall performance of the aircraft. So, which means that a designer as to carry out at trade of between internal and external deceleration depending upon the design condition of the intake, which is usually during cruise of the intake of the aircraft which is when aircraft operates for the maximum duration.

So, trying to have larger amounts of pre entry compression could lead to spillage on one hand and the other hand it may also lead to issues with the internal diffusion itself under other operating conditions like flow separation within the diffuser and therefore it is always a trade of between how much amount of pre entry compression we can have as compared to the overall compression of the intake itself. We will now quickly look at how we can have understood the different modes of operation of subsonic intakes.

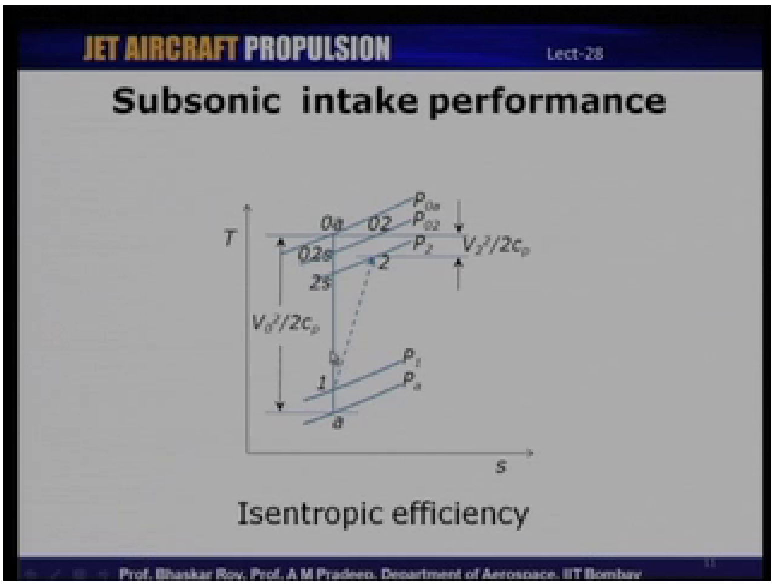
We will now look at how we can evaluate the performance of intake and what are the performance parameters, which we can associate with an air intake. We already discuss about one of these parameters in some of earlier lectures during cycle analysis and that was the isentropic efficiency. So, efficiency or Isentropic efficiency is one of the parameters using which one can evaluate the performance of intakes but there are other parameters as spell like pressure ratio and distortion.

(Refer Slide Time: 30:13)



So, let us take a quick look at some of these performance parameters and these performance parameters are valid for both subsonic as well as supersonic intakes. The three parameters which are normally used, one is the isentropic efficiency which we have discussed. We will also discuss that quickly in today's class when there is stagnation pressure ratio or sometime referred to as pressure recovery and then there is a distortion coefficient.

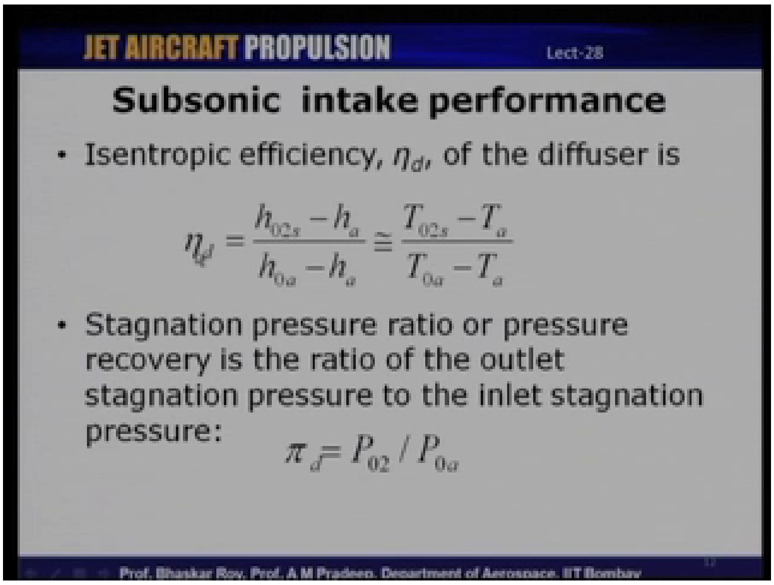
(Refer Slide Time: 30:41)



So, Isentropic efficiency we have already discuss this in the earlier class in some of earlier lectures refers to the difference in stagnation pressures leading to or the efficiency is basically defined in terms of the temperatures that corresponding that correspond to the difference in stagnation pressures as a result of loss in stagnation pressure within the diffuser. So, you can see that P 0 2 and P 0 a are two pressure lines stagnation pressure lines, P 0 2 corresponds to the actual pressure stagnation pressure, P 0 a corresponds to the ideal stagnation pressure; both of them fall on the same stagnation temperature line.

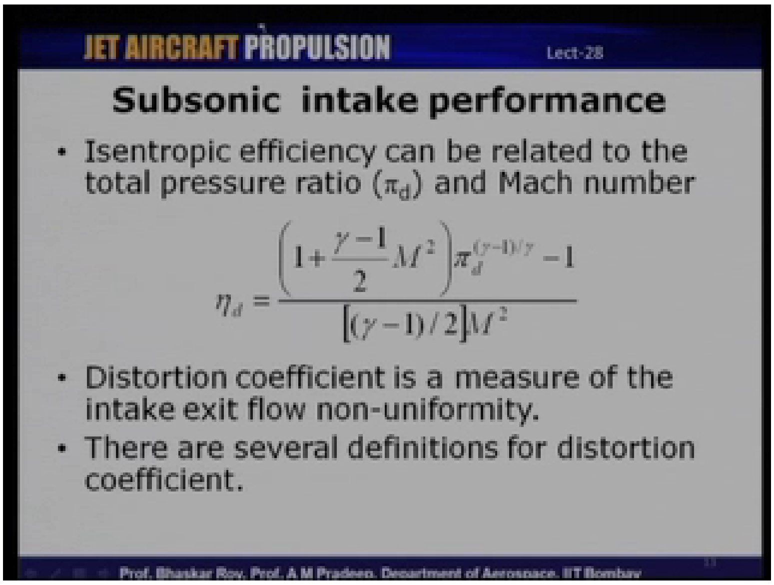
There is no change in stagnation temperature but there is a change in the stagnation pressure. So, we are going to define efficiency based on these stagnation temperatures which correspond to a process which would have been Isentropic.

(Refer Slide Time: 31:41)



So, the efficiency of the diffuser is defined as h 0 2 as minus h a divided by h 0 a minus h a. So, h 0 2 h as corresponds to this point on P 0 2 which is distinct actual stagnation pressure and h 0 a corresponds to the ideal stagnation enthalpy, which is falling on the ideal stagnation pressure line. So, this simplifies to T 0 2 S minus T a divided by T 0 a minus T a. So, this is how we have we define Isentropic efficiency of a diffuser, which is defined in terms of temperatures, but it is not because of loss in stagnation temperature, but it is because of loss in stagnation pressure. The other parameter is stagnation pressure ratio or pressure recovery which is simple the ratio of the outlet stagnation pressure to the inlet stagnation pressure P 0 2 by P 0 a.

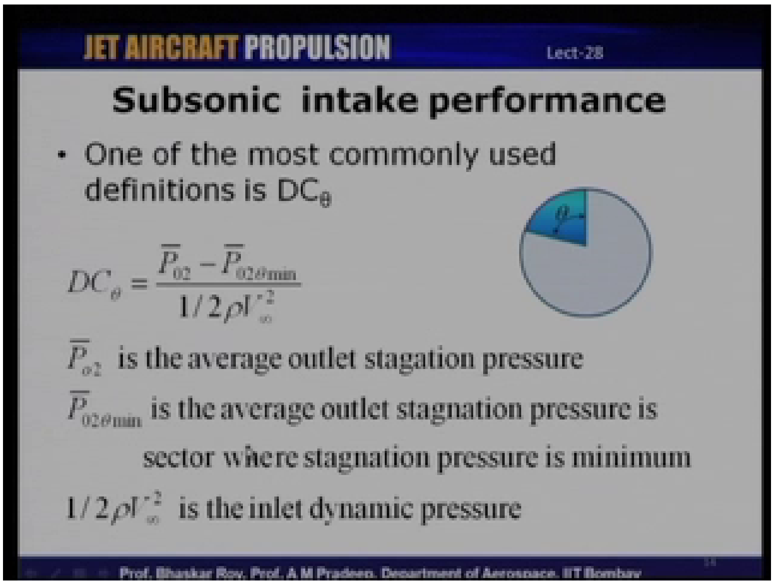
(Refer Slide Time: 32:43)



So, we can relate these two stagnation efficiency isentropic efficiency and stagnation pressure ratio. So, if you simplified I think you have carried out the exerciser earlier. Diffuser efficiency is would be a function of the Mach number and this stagnation pressure ratio. So, if diffuser efficiency would be 1 plus gamma minus 1 by 2 M square multiplied by pi d which is stagnation pressure ratio raise to gamma minus 1 by gamma minus 1 divided by gamma minus 1 by 2 M square.

The other performance parameter which is used is known as the distortion coefficient which is a measure of the intake exit flow non uniformity. Because we have discuss that the flow exiting the compressor of exiting the intake as to be uniform non uniformities in the intake exit flow will drastically effect the compression performance and therefore, the engine performance as a whole. So, how do we measured or quantify this non uniformity?

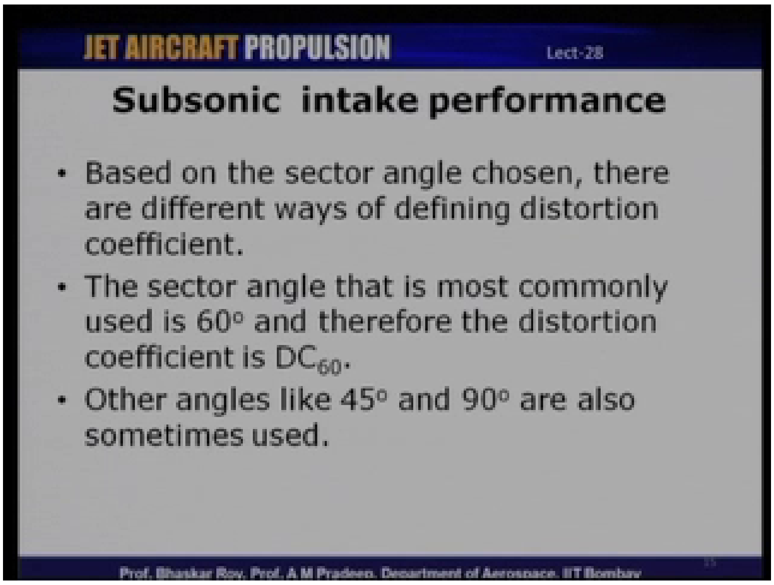
(Refer Slide Time: 33:48)



There different definitions for distortion coefficient one of the most commonly used definitions is known as DC subscript theta where DC stands for distortion coefficient. DC theta is briefly define as there difference between the average stagnation pressure at the exit of the diffuser minus the average stagnation pressure in sector theta where this stagnation pressure is minimum divided by half rho v infinity square. So, P 0 2 averages is the average stagnation temperature stagnation pressure the outlet of the diffuser. If we taken an average let us say this is the diffuser outlet cross section. You taken an average of this stagnation pressure over this entire cross section that is P 0 2 bar P 0 2 theta minimum is the average stagnation pressure in a sector where this stagnation pressure is minimum.

So, we define a sector theta and measure stagnation pressure in that average stagnation pressure in that scan the sector over the entire circumference and for that sector where the average stagnation pressure is minimum is what is used here. This divided by the inlet dynamic pressure gives us DC theta. So, in this case theta I have shown here corresponds to that sector where the average stagnation pressure is minimum. So, which means that we will have to take this scan this entire circumference for sectors theta where the pressure is minimum.

(Refer Slide Time: 35:34)



So, based on this we can have different ways of defining DC theta depending upon the sector angle chosen and one of the most common angles used is sector angle 60 degrees and that is by DC distortion coefficient for that is known as DC 60 where 60 corresponds to the sector angle. There are other angles which have also used sometimes 45 degrees and 90 degrees in which case it would be DC 45 and DC 90. But DC 60 happens to be or has been proven to be most common way of defining distortion coefficient and it is widely used by the engine manufactures all over.

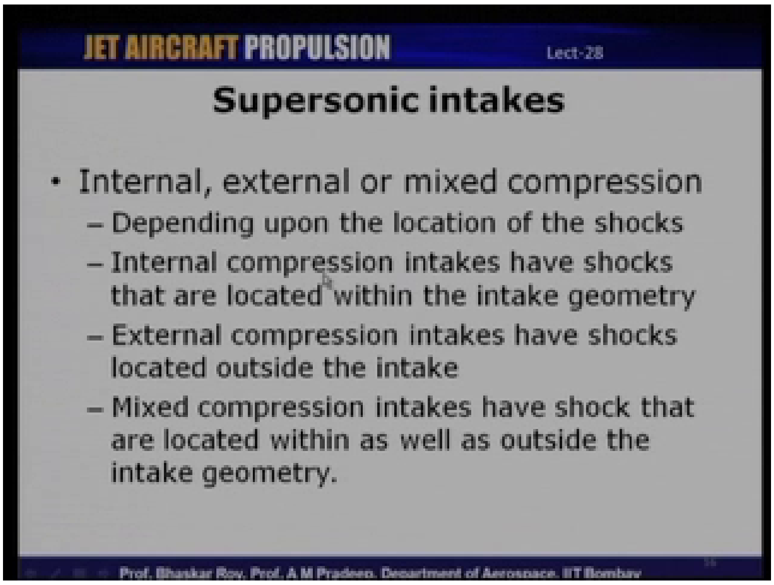
So, an engine when it is supplied comes with this parameters the intake comes with these parameters one is the pressure recovering, which is related to the thrust because lower the pressure recovery obviously, it will affect the thrust correspondingly. DC 60 tell us what is the amount of distortion that this intake will deliver and every engine will have a certain level or limit of the DC sensitivity beyond which the engine operation might get affected. So, the intake designer as to keep these parameters in mind while designing the intake. So, we now move on to supersonic intakes we have discussed about subsonic intakes so far of course, all the performance parameter I am discussed just now is valid also for supersonic intakes.

Let us look at some of the issues related to supersonic intake operation like what is mean by starting and what are critical modes of operation of intakes and so on. Now during our last lecture we have I mentioned about three types of intakes internal compression, external compression and mixed compression intake that is one way of classifying supersonic intakes.

So, will discuss our discussion in today's lecture will be based on this classification of intakes. So, internal compression basically involves internal compression intakes involves compression, which is taking place entirely within the diffuser geometry itself and that is the shocks that eventually lead to deceleration would occur within the surface of the intake itself.

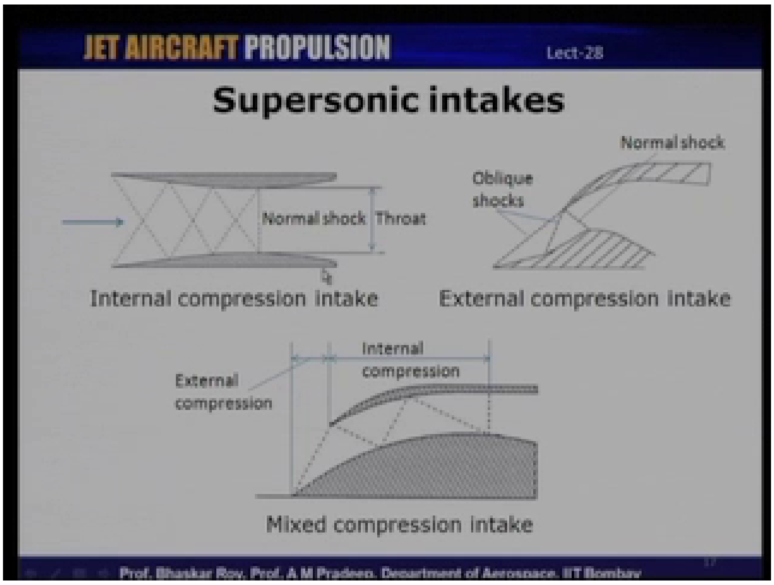
External compression involves shocks which are outside the geometry of the intake next compression is a combination of these two. So, depending upon the type of intake the flow problems associated with that our slightly different but one of the problems is usually present in all the three that is basically known as starting of an intake will discuss that in little bit detail.

(Refer Slide Time: 38:15)



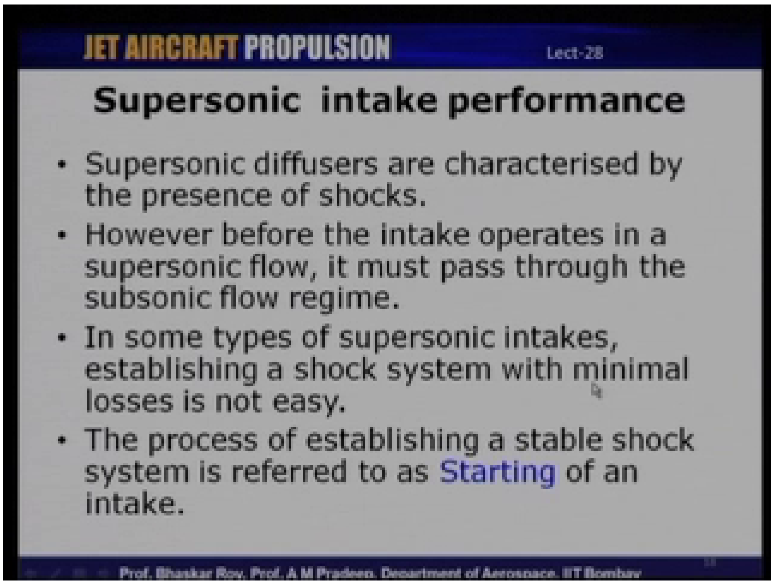
So, internal, external and mixed compression intakes.

(Refer Slide Time: 38:18)



Let us look at typical geometry of these types of intakes this is an internal compression intake. You can see all the shocks structure and shock system is within the intake itself or several oblique shocks eventually ending in a normal shock were which is basically the throat of the intake in an external compression intake. We have oblique shocks ending in a normal shock all of them are outside the intake itself. Of course the ramp is still outside ramp is the one which leads to formation of this shocks and this is the normal shock in this case their two oblique shocks and normal shock. Mixed compression intake involves part of the compression which is external this is external compression and part of the compression which is internal this part of the compression takes place internally.

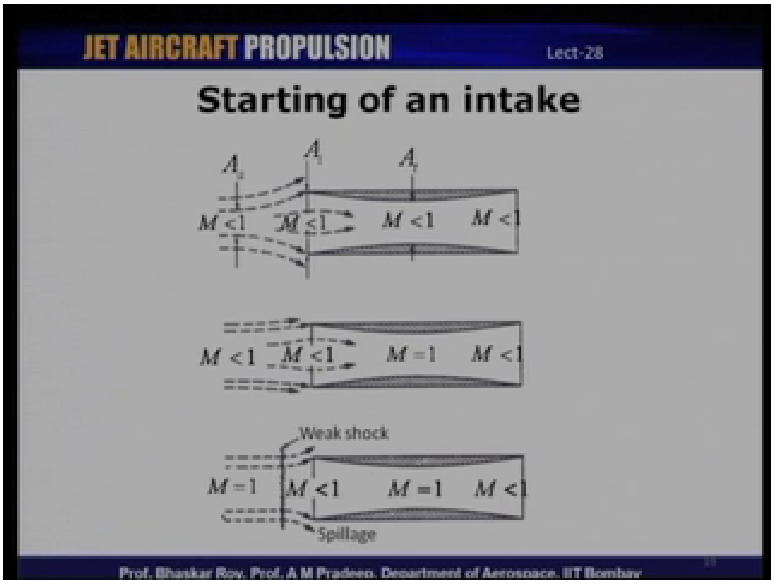
(Refer Slide Time: 39:09)



Now, in supersonic intake as we have seen or characterized by presence of shock and the but these intakes have to operate right from subsidy very low subsonic speeds all the way to supersonic speeds and which means that we will have to established a shock system as the intake approaches supersonic or as the intake reaches supersonic speed and this is often a bit of problem trying to establish a stable shock structure. So, this process by which one would as established as stable shock structure for stable operation or study operation of the engine is known as starting of the intake.

That is one would need to always start an intake where in one as to established a stable shock structure which leads which results in minimum pressure loss and that is in some types of intakes it is a big challenge to establish say a stable shock structure. So, will discuss about one of the geometries where this problem is more pronounced that in internal compression intake, which involves shocks within the diffuser geometry itself and will discuss about one set geometry and this process by which the shocks structure is established is known as starting of any intake.

(Refer Slide Time: 40:26)

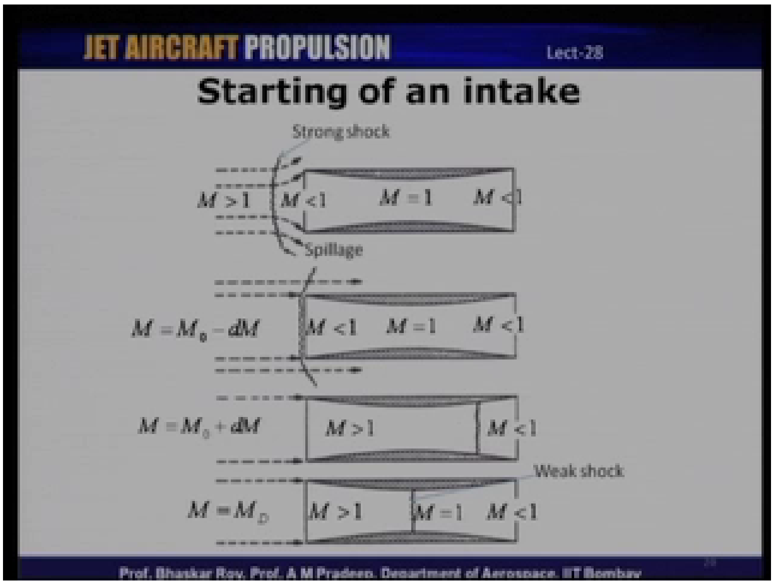


So, let us look at starting problem of an intake. Now this is an internal compression intake. So, as the engine begins its operation from very low subsonic. So, you can see Mach number is less than one and it continues to remain less than one the intake as just started. This A corresponds to the capture area this is the intake entry area and this is the throat area. Now as the engine accelerates at a certain Mach number which is still subsonic free stream Mach number is still subsonic the flow might reach sonic speeds at the throat. But continue to remain subsonic even downstream of that because the back pressure is not low enough.

As we accelerated further as the engine operate approaches sonic speeds as the flight Mach number approaches sonic speeds there could be an occurrence of a weak shock. Because Mach number as now reached one there is weak shock which is ahead of the intake itself downstream of the shock Mach number is subsonic because it is subsonic in this section because which is converging the flow accelerates and it might reach sonic speeds at the throat and continuous to remain subsonic downstream.

For presence of this weak shock also means there would be downstream of the shock it is subsonic, but before that it is supersonic or sonic and so the stream lines are straight because in as sonic or supersonic flow information does not travel upstream and therefore, all this stream lines up streamer straight. After the weak shock the flow gets diverted and that leads to spillage occurring at this particular Mach number.

(Refer Slide Time: 42:11)



Now, as we increase the Mach number further at supersonic speeds this weak shock becomes a strong shock, and it takes a curvature and this is known as a bow shock and downstream of the shock its subsonic Mach number; Mach number become sonic at the throat and it continues to remain subsonic. What might think why not operate the intake in this condition, there two problems of operating an intake under this condition, one is the fact that there is strong shock leading or ahead of the intake which means the stagnation pressure loss is a substantial.

The other problem is that there is substantial spillage taking place leading to external drag as well. So, one would not want to operate the intake with a strong shock a head of the intake. So, if let us say we change the Mach number from its supersonic Mach number we increase the Mach number or decrease the Mach number. Let us say we have a Mach number which is which is a design Mach number which is slightly less than the design Mach number in which case the shock will now get attached to the leading edge of the intake. So, this shock is now attached right here at the leading edge downstream of that the flow is subsonic it reaches sonic speed at the throat and then the subsonic again.

This is again not desirable because the pressure losses here this spillage is minimal there is no spillage here. Because you can see the capture area is exactly equal to the intake entry area. So, there is no spillage, but the stagnation pressure loss is still persists in this case. So, if we got accelerated further from the design Mach number to a slightly higher Mach number then we can have a shock, which will move into the intake. Now the shock system is normal shock is never stable in a convergence section, but it can operate or it can have attain a stable position in a divergence section. So, we now have supersonic Mach number all the way here up to the normal shock which is in the divergence section.

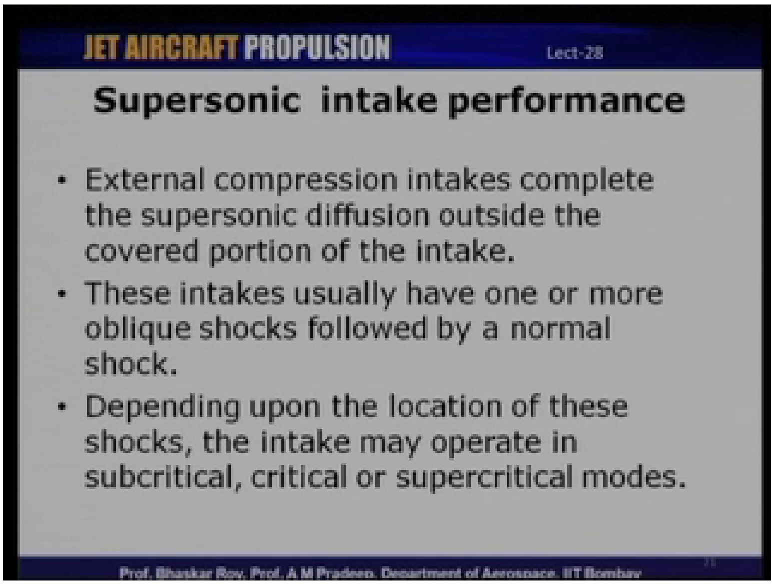
And then sub downstream of that we have subsonic Mach number and after this if decelerate and bring the engine back to its design Mach number within have now this same normal shock which moves slightly upstream and attains a stable position just after the throat. So, just around the throat we have a normal shock which is very weak. It is weak because of the fact that is very near the throat that the Mach number reaches unity and therefore, because it is a weak shock there is the pressure losses across the shock is minimal the other advantage is that because its supersonic all the way up to the throat there is no spillage because the capture area and the intake entry area are the same.

So, as the Mach number reaches its design Mach number we have a weak shock here right after the throat subsequent to that we have a subsonic flow. So, this is the condition ideal condition that one would like to have before the intake is set to have been started. So, when we say that the intake as been started we mean that this a normal shock which is operating or which as attain the stable position right after the throat and it is to kept right after the throat because that is where the Mach number is minimal. So, the pressure loss is across the normal shock is minimal in under this operating condition there is no spillage also under this condition.

So, this is the starting problem. So, which means that though I have explain it in simple terms in actual engine it is not that simple to establish a stable shock system by either accelerating beyond the design Mach number and so on. The other ways of implementing this pi changing throat area and so on I have not discussed at here. But in simple terms establishing stable shock structure right after the throat is very essential for efficient operation of the engine.

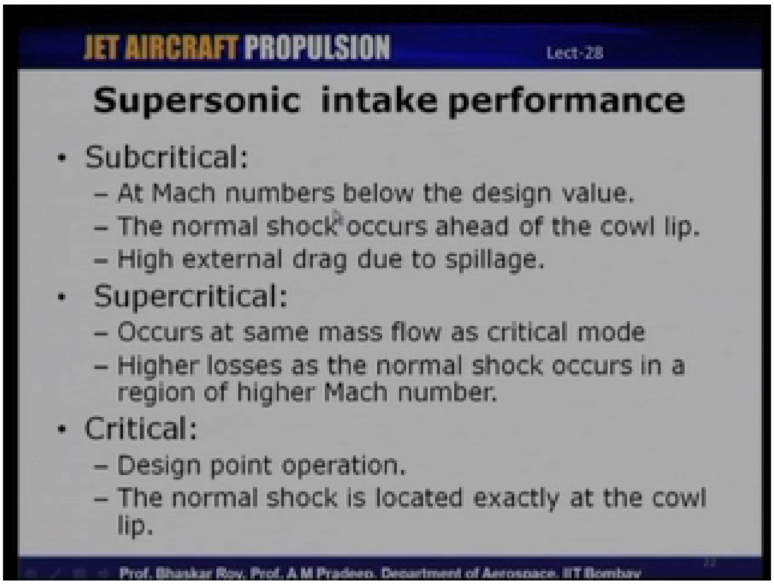
Because that is why we have lower minimal tool pressure loss without any spillage and this is a problem which is more servers in these types of intakes which are pitot type internal compression intakes they may also be present in some of the external compression or mixed compression intakes. But there are not as severe as what we have discussed for this case.

(Refer Slide Time: 46:45)



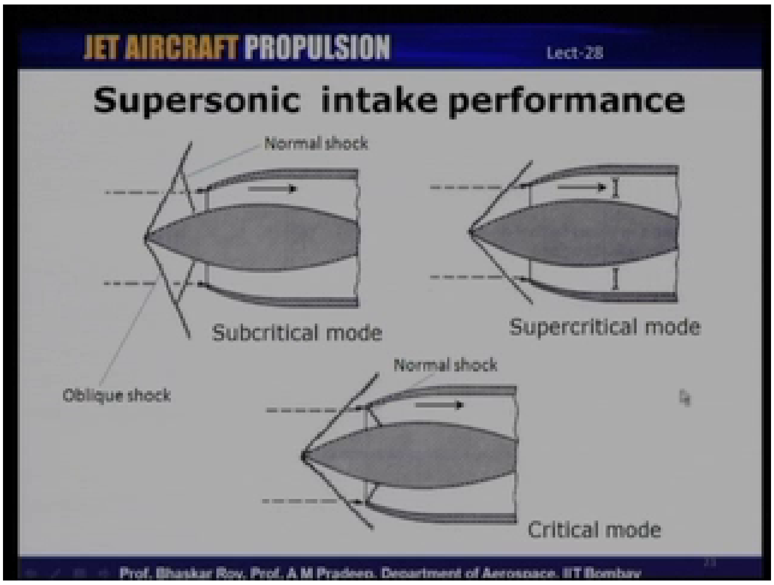
So, will now discuss about external compression intakes and associated problems with that. In external compression intakes the compression takes place outside the covered portion of the intakes and you usually have one or more oblique shocks followed by a normal shock and depending upon the location of the shocks the intake may operate in sub critical mode, critical mode or the design mode or super critical modes of operation.

(Refer Slide Time: 47:12)



Sub critical mode is when Mach number at Mach numbers below design value. The normal shock and the oblique shocks are placed well ahead of the cowl lib there is a high external drag do to spillage under this operation. In super critical mode of operation which occurs at the mass flow as critical mode higher losses occur because the normal shock will occur in region of higher Mach number. I will explain this in the next slide critical mode is design mode of operation normal shock is located exactly at the cowl lib.

(Refer Slide Time: 47:41)



So, these are the three modes of operation sub critical mode the oblique shock and the normal shock are ahead of the cowl therefore, there is spillage and losses associated with that. super critical mode is when the normal shock as now moved downstream of the throat, which means that the flow is supersonic here all the way up to normal shock and therefore, in a supersonic flow a divergent this is the convergence section here in this case leads to acceleration of flow, which means that the Mach number keeps increasing from the intake entry all the way up to normal shock.

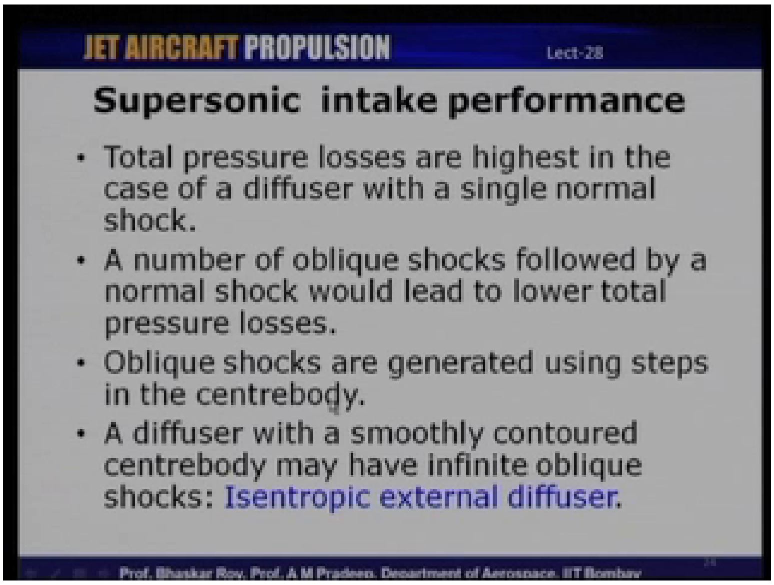
So, the normal shock is now occurring in Mach number which is higher than much higher than Mach one. Therefore, stagnation pressure loss is higher in super critical mode. Critical mode is when the normal shock occurs exactly at the cowl lib here. And therefore, and that is the throat therefore, the losses across this normal shock will be minimal. So, this is how this is the operating condition for which the intake would have been design for so that normal shock occurs right at the cowl lib. Now operate section of this type of intake is also tricky.

But usually the position of the ramp is adjustable it will not be fixed ramp it could be adjustable and depending upon the mode of operation of the engine the ramp position is adjust so that adjusted so that the normal shock can be fixed at the cowl lib itself and that is where it operates under critical mode of operation. So, total pressure losses will be highest in the case as we have discussed in the case of a diffuser which as just one normal shock ahead of it. We have discussed that when we are talking about starting of an intake if added strong oblique shock at right ahead of the intake entry total pressure losses would be very high.

Because we have shock strong shock which is an ahead of the intake total pressure losses are high which means that a better option would be have to multiple shocks multiple oblique shocks eventually having ending up in a normal shock. So, that before the flow end entries or hits the normal shock its Mach number is low enough. So, that loss across the normal shock is minimized. So, instead of decelerating the entire supersonic flow to subsonic through one normal shock it is a normal practice to use multiple oblique shocks eventually ending in a normal shock.

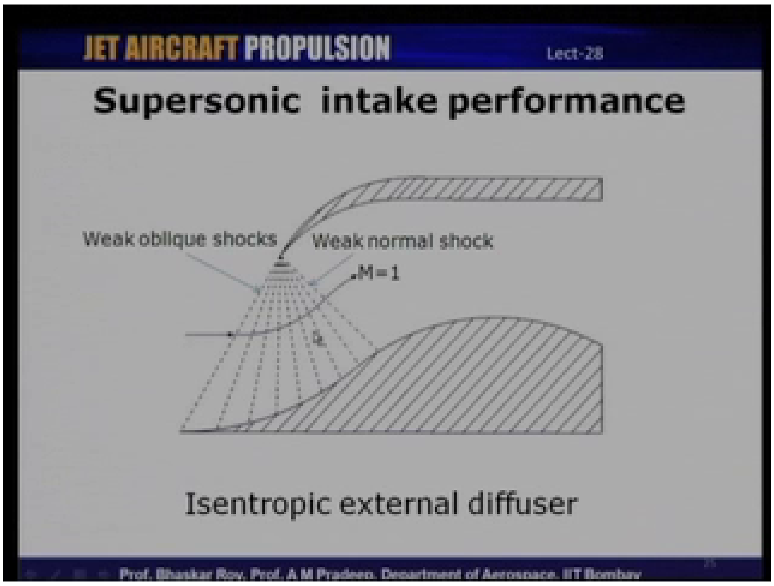
So, that losses can be minimized and this is usually achieved using ramps I have shown one example where we had a ramp with two steps resulting in two oblique shocks and then one normal shock. So, if we increase this infinitely if you have infinite number of normal shock oblique shock and then normal shock then the losses can in this case set to be 0. This is possible if we have a conduit ramp which will result in generation of infinite number of oblique shocks which are very, very weak and then normal shock. So, in this case the flow can be set to be Isentropic, if you of course, assume that friction losses are minimal. In such a diffuser is known as a isentropic external diffuser where the infinite number of oblique shocks and then normal shock the losses across the shocks are minimal.

(Refer Slide Time: 51:10)



So, oblique shocks in a diffuser which as a very smoothly conduit center body may have infinite number of oblique shocks and that is known as an Isentropic external diffuser.

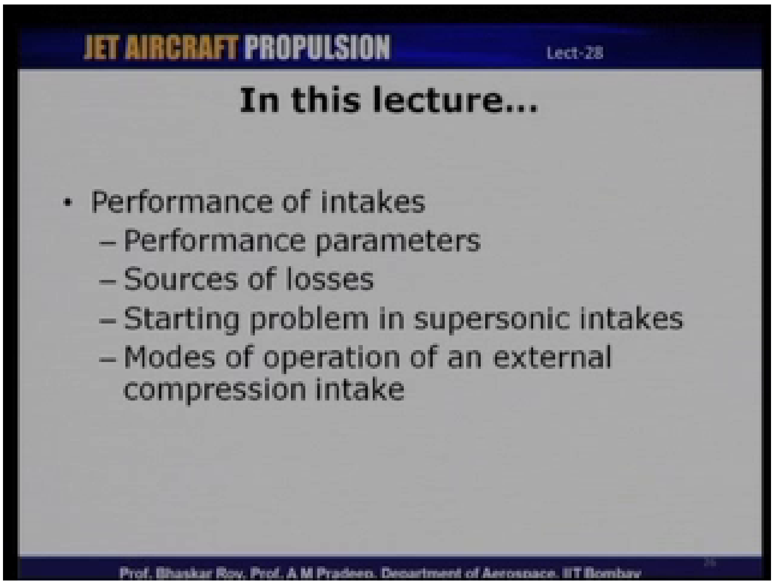
(Refer Slide Time: 51:19)



So, this is just an illustration of an isentropic external diffuser. If we are if we are able to conduit this center body in such a way that we have infinite oblique shocks which are weak and then weak normal shock, then a supersonic flow can be decelerated through all this infinite shocks eventually to subsonic Mach number through this shock infinite shock system.

Now though theoretically this is very much possible a such diffuser would be extremely sensitive to the location of ramp itself that is any small change in the operating condition would requires occurs point change in the ramp location, which means which is physically not feasible to implement and that is why we do not really have such an intake operational and so because it is extremely sensitive to the operating condition theoretically it still possible to have an intake which as the shock system and it is still close to Isentropic diffusion taking place through this shocks.

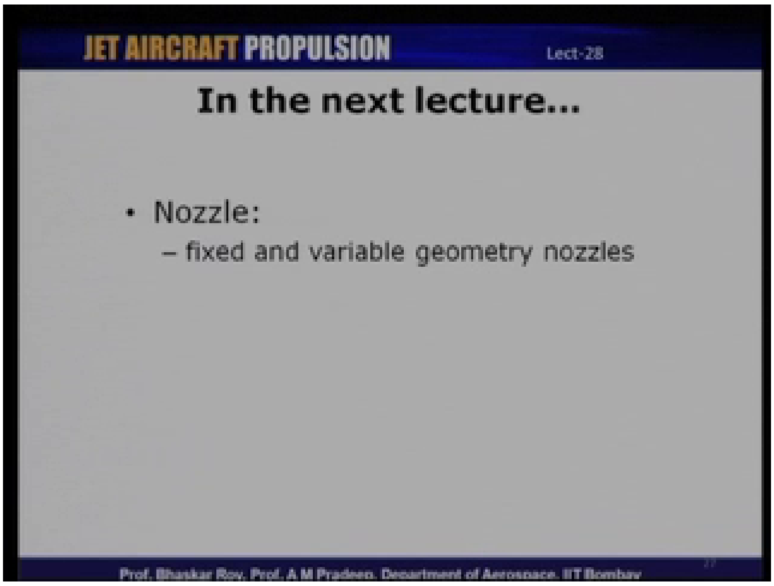
(Refer Slide Time: 52:38)



So, in today's lecture I am trying to wind up today's lecture and will just look at what we have discussed in today class. We started out discussion with subsonic intakes which is talked about subsonic intakes and how we can evaluate performance of subsonic intakes. We have discussed about different modes of operation of subsonic intakes especially what happens under extreme operating conditions like takeoff or cruise discussed performance parameter which is valid for both subsonic and supersonic intakes and these sources of losses in these intakes.

We have discussed in brief about starting problem in supersonic intakes and we also discussed about different modes of operation of an external compression intakes. So, these are some of the topics that we had taken up for discussion in today's class and that will bring us to the end of this chapter on intakes. So, last two this lecture and the previous one we had discussed about the intakes there operation different types of intakes and problems associated with intake operation and so on. In the next lecture, we will discuss about yet another important component of an engine which is the last component of an engine the intakes constitute

(Refer Slide Time: 53:43)



The first component of an engine diffuser of well nozzles forms the last component of an engine. So, in the next lecture will shall be discussing about nozzles. We will discuss about different types of nozzles fixed, and variable nozzles, and in a similar manner as we discussed for diffuser will discuss about types of nozzles. We will also discuss about problems associated with some of these nozzle operation. So, this we shall take up in the next lecture when we shall start discussing about nozzles, and different types of nozzles.