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

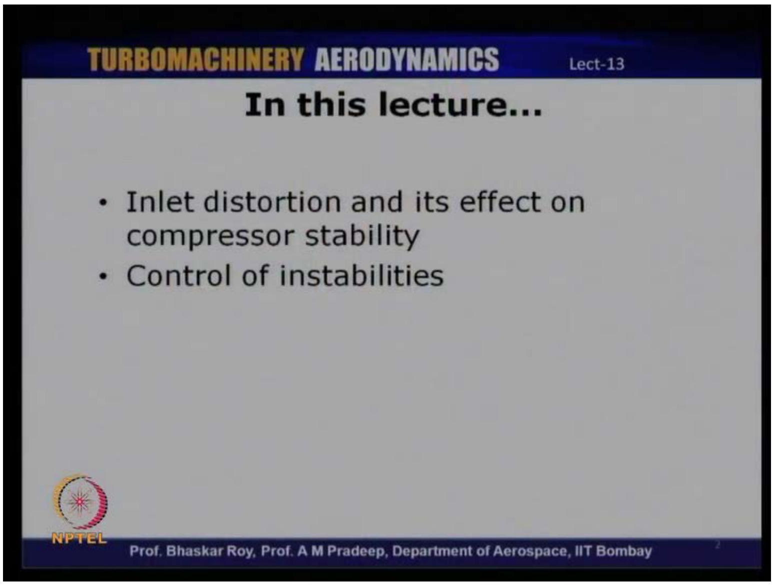
Lecture No. # 13

Inlet Distortion and Rotating Stall, Control of Instability

Hello and welcome to this lecture number thirteen, of this lecture series on Turbomachinery Aerodynamics. In the last class, which was lecture number twelve, we had quite some discussion on what happens when a compressor is operated under extreme off-design conditions, the onset of what are known as the instabilities. So, there up, as we have discussed there are primarily two modes of instabilities. One is the rotating stall. And, when rotating stall becomes too severe, then the compressor is likely to encounter surge. Well, it is also possible that compressor might enter directly into surge, if the conditions are favorable for occurrence of surge. And, of course rotating stall might still be there, but it is too small to be detected and one might encounter direct surge. So, that is a possibility that also occurs in certain types of compressors. And, as we have seen, the occurrence of these instabilities depends upon a variety of parameters including the geometry, the design and performance characteristics of a particular compressor. So, it is kind of not really easy to generalize and say that compressors will stall or surge in a particular manner.

What we have also seen is that, there are also different types of inception of rotating stall. One might have a spike initiated stall or an abrupt stall, where the compressor suddenly jumps into stall. Or, one might have what are known as model inception of stall, where there is a progressive inception taking place. So, these are also possible in different compressors that depending upon the compressor, geometry and design. So, what we are going to discuss in today's lecture would be basically about again instabilities, but also certain aspect which can trigger instabilities.

(Refer Slide Time: 02:19)



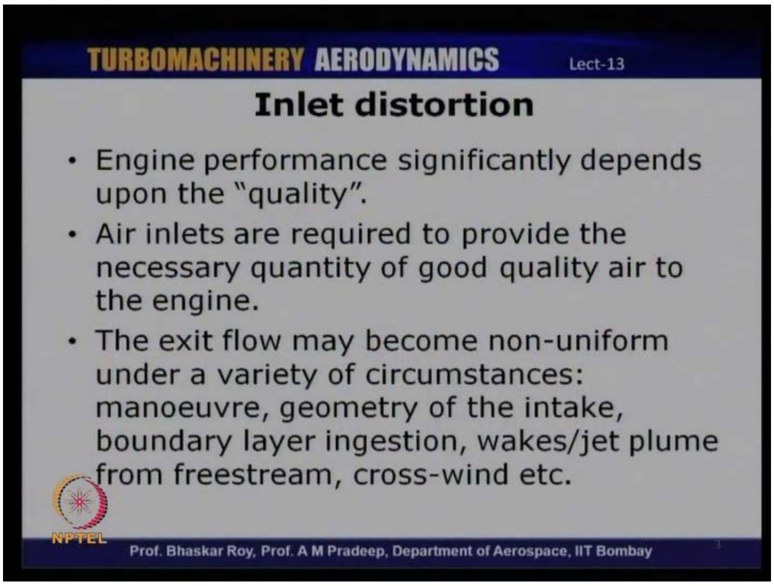
These are to do with the inflow quality and inlet distortion as it is called, and its effect on compressor stability. We will be discussing in great detail about inlet distortion and its effect. We will subsequently, also be discussing about how we can control these instabilities? Most of the control mechanisms that we will discuss have not really been implemented on an actual engine due to practical limitations because they are still in a developing stage. And, we do not really have a technology, which is so matured that it can really be used in an engine for control of instabilities.

Some of them are being used in some way or the other, but they are very few. So, these are certain topics that we will be discussing in today’s class. So, before we take up the first topic, which is to do with inlet distortion, let us try to understand what we mean by an inlet distortion and why is it so significant.

Now, as we know the engine performance as a whole is in some way limited by the compressor performance. That is, compressor holds one of the keys to engine performance to a stable engine performance or operating condition. And, the compressor performance is highly dependent on what kind of flow the compressor receives at its inlet. That is, depending upon what kind of flow enters into the compressor, the compressor behaves in particular manner; which means that if the flow, which is entering the compressor is very clean and very uniform, then the compressor is likely to behave in its best possible way. Whereas, if the inlet itself is highly non-uniform, you have all kinds of non-uniformities that enter into a compressor, then it is possible that the compressor may not be operating in the right… may not really operate in the way it should have been.

So, inlet is one of the components, which is fixed ahead of a compressor. That is, you have a certain component which delivers mass flow rate into the compressor, and that component is known as the intake or inlet; depending upon the terminology that is used. So, the compressor performance will therefore, depend heavily upon how the inlet behaves or the intake behaves under different operating conditions. That is, if the out flow from the intake is highly non-uniform, obviously, then that is going to have a very drastic effect on the compressor performance as well. So, inlet performance or intake performance will also determine the performance of the compressor in some sense or the other; which is why we need to understand the effect of the intake performance on the operation of the compressor itself. And, that is one of the primary topics of discussion in today's lecture.

(Refer Slide Time: 05:18)



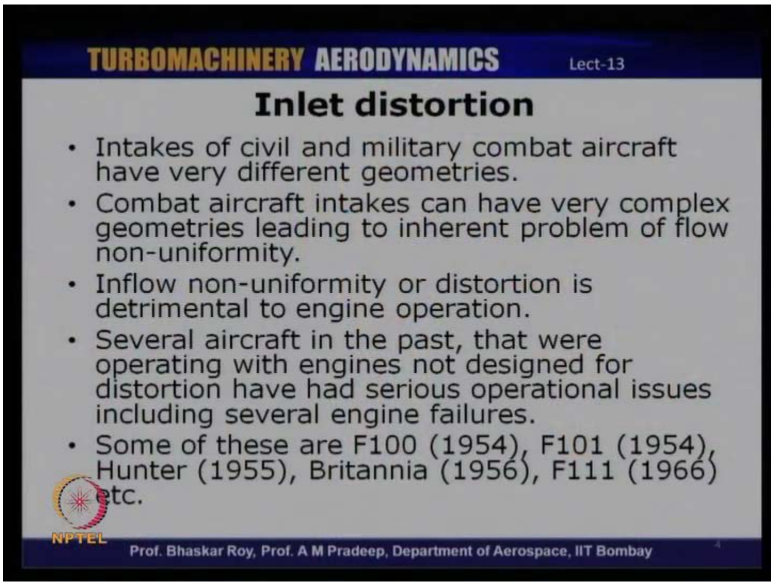
So, as I mentioned, engine performance significantly depends upon the "quality" of air; well, the quality I have put here in inverted quotes because the quality here, refers to the flow uniformity that is entering into the compressor. So, that is why it is been referred to as quality of flow. And, the primary objective of the inlet or the intake is to provide necessary quantity of good quality air to the engine. So, this is very important that the engine not only requires a certain amount of mass flow that will be the quantity of air intakes or engines also require good quality of flow. We are going to quantify or we are going to specify what quality means;

basically to do with distortion. And, so you might wonder, why is it that an intake performance or intake outflow becomes non-uniform. Well, there are many several reasons, which can lead to non-uniformity of the intake exit flow. One of the major reasons is especially in a military aircraft, when an aircraft is undergoing very severe manoeuvers, we… when the aircraft undergoes all kinds of manoeuvers, then part of the intake becomes shielded from the flow and therefore, the flow entering the intake and subsequently leaving the intake becomes highly non-uniform.

So, that is one of the ways in which the intake exit flow can become non-uniform. Well, there are several other reasons. The other reason; especially again to a military aircraft is when the intake is itself having a very complex shape. I will probably be discussing some of these shapes in later slides. So, when the intake has complex shapes, then the flow inherently becomes non-uniform because of the development of what are known as secondary flows. So, secondary flows develop when the flow encounters curvatures, which is through if the intake itself has certain curvature. And, the other possible reasons are, when the intake is located very close to the fuselage and then there could be a growth of boundary layer, which can develop from the fuselage and might enter into the intake. So, the intake might actually ingest some. In fact, in certain very complex shapes of intakes, you might have lot of very thick boundary layer entering into the intake and subsequently the compressor. So, that is another source of non-uniformity. That is likely to, get into an intake and subsequently the compressor. And, you can also have situations where an aircraft is operating under high turbulence or cross wind or in the wake of preceding aircraft.

And, all these can lead to non-uniformities in the flow, which eventually will affect the compressor performance. And, that is what we are going to discuss in detail today.

(Refer Slide Time: 08:21)



And, there is also a dependence on the kind of engine that we are talking about. That is, as we know, intakes of civil as well as military aircraft have very significantly different geometries. And, especially in a combat aircraft, the geometry itself is so complex that inherently their non-uniformities from the exit of the inlet. And, that is basically to do with the geometric shape itself. And, so this non-uniformity that enters into the compressor has very severe effect on the compressor performance. And, it affects the compressor performance in a very drastic way. And, in the past there have been several aircraft, which have actually had serious operational issues and failures, primarily because the engine was not really designed for withstanding very high levels of distortion; so, in the earlier days of engine development, when designers were not really aware of the fact that, the compressor performance can be significantly affected by the quality of air that enters the compressor. And, in those days, the knowledge about the fact that inlet distortion can also cause engine failure due to surge was not really known. And therefore, lots of aircrafts in the past have had very serious operational problems. And, many of them had engine failures because of the presence of distortion. Some of these aircrafts like the examples given here F100 in 1950s; quite a few of them in the 1950, F100, F101; the Hunter in 1955, Britannia in 1956 and F111 in 1966.

All of these aircrafts have had issues with inlet distortion, seriously affecting the performance of the compressor and therefore, the engine. So, when they realize that there is something to do with the quality of flow affecting the engine performance through the compressor surge, it was, then that they realized that there is a significant effect of the inflow quality on the stability of the compression system. And, of course there have been lot of studies on this aspect of inflow distortion and quality on compressor performance. They were since. And, of course our knowledge about inflow distortion and its effect on compressors is much better now. And therefore, most of all the engine manufacturers really specify a certain level of distortion, which a certain engine can withstand without undergoing or without encountering instabilities.

So, they specify a certain amount of parameter which we will define subsequently, which is to do with the tolerance of an engine to a certain level of distortion. So, all engines come with this tag, saying that this engine has been designed to withstand so much amount of distortion. So, if the inflow distortion is greater than that, then the engine is likely to encounter operational issues. And, so that is something that is provided to the air frame and intake designers because the intake designers would need to know, what is the extent to which the exit flow can be distorted for this particular engine; because the engine manufacturers have always specified the percentage of distortion that this engine can withstand. So, that will kind of help the intake designers and air frame manufacturers, who will eventually integrate the intake and the engine. To kind of decide, what kind of geometry is to be used and how we can minimize distortion to enable this intake to meet this particular engine requirement in terms of distortion. So, distortion coefficient as we will define later is that distortion is basically quantified with what is known as distortion coefficient and that tells us the extent to which an engine can withstand certain amount of distortion.

(Refer Slide Time: 12:55)

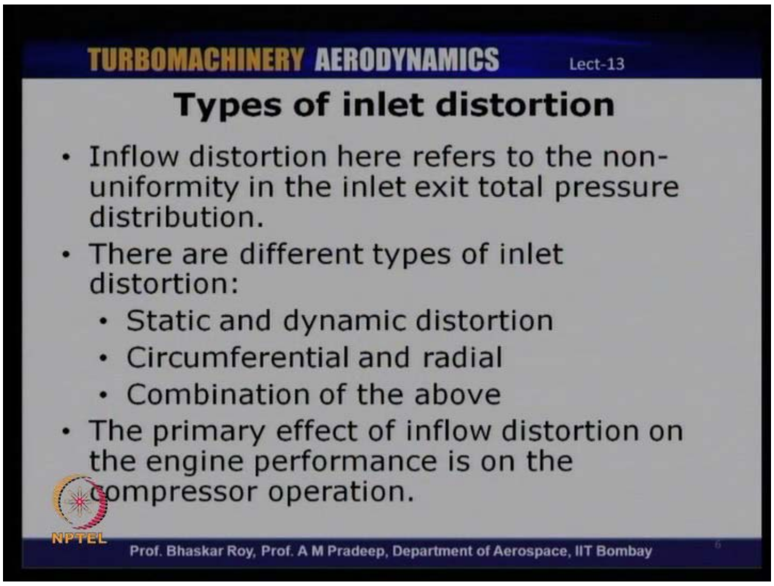
Now, let us take a look at two different types of aircraft. And, consequently the different types of intake. And, I guess you might have seen both of these types of aircraft. One is a normal transport aircraft, which has these wing mounted engines. You can see there are two engines here. And, you can actually see the compressor, the fan of the engine directly. The intake here is what is shown within this. So, there is a very short intake for typical subsonic aircraft. And, so here, the problem with distortion is not that severe. Of course, I am not saying that there is not distortion issue. There is definitely an issue with distortion even for such aircraft, but it is much more severe for these kinds of aircraft, which is a military aircraft. And, military aircraft obviously, has entirely different type of intake mainly because of the fact that the engine is mounted within the fuselage of the aircraft.

So, here is the engine as you can see. Well, you cannot really see an engine in a military aircraft. This is the engine of the aircraft. So, this is the engine of the aircraft and there are two intakes. You can see one intake here and another one here, which feed into the engine. And, you can see the difference between the mounting of this particular engine and the intake as compared to military aircraft. So, here you can see that the intake is very close to other surfaces like the wing and the fuselage. And so, there is a possibility that you could have boundary layer, which is developing from these surfaces entering the intake; which is why, you can see that there is a small gap between the fuselage and the intake; so that, the boundary layer growth can be actually cut off. And, you do not really have a very thick boundary layer entering the engine. The other aspect to be noted is that, the engine and the engine center line and the intake center line are not the same. So, the engine and intake are actually off set. Therefore, there is an inherent curvature for the intake, which is not there in a subsonic transport aircraft where the intake is straight and axial symmetric and it has a center line, which coincides with that of the engine.

So, here military aircraft intakes will inherently have much higher geometric complexities. And, consequently military aircraft intakes will have lot more problems to do with inlet distortion. And, that is why, military aircraft engines are designed to kind of withstand slightly higher levels of distortion as compared to normal civil aircraft, where you will not really expect very high levels of distortion from the intake. So, the basic operation of such intakes and therefore, the outflow quality from these intakes are themselves different.

So, having now understood the significance of distortion and the effect of distortion on the engine performance through the compressor performance, let us now take a look at what are the different types of distortion. And, so it is also possible that distortion can occur in different forms. And, so we will take a look at what are the different types of distortion that are possible and how we can quantify these different types of distortion.

(Refer Slide Time: 16:28)



So, here when we talk about distortion, we are basically referring to the exit total pressure distribution. You may also have distortion in terms of temperature. We are not really talking about temperature based distortion or non-uniformity. We are primarily referring to pressure based distortion or non-uniformity. And, there are different types of this non-uniformity. One may have static or dynamic distortion. Static is time independent or steady state distortion; that is, distortion does not change with time. Or, you may have distortion, which is dynamic or it is time variant, or it changes with time, or it is unsteady.

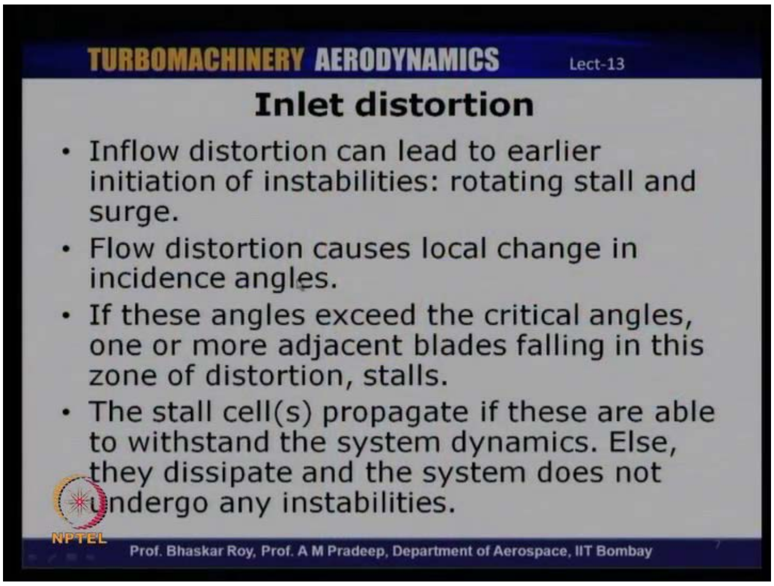
Well, these are of course, the static distortion is an idealized version; so, called idealized version. The flow in an intake is never very steady. You may always have certain amounts of unsteadiness and therefore, static distortion is really a kind of an idealization. You may also have distortion, which is either circumferential or radial. Circumferential refers to distortion. Only in the circumferential plain and radial distortion is non-uniformity in the radial direction. The third possibility is, of course a combination of all of this. You may have static circumferential distortion or you may have dynamic distortion, which is circumferential. You may also have distortion, which is both circumferential as well as radial. But, having understood these different types of distortion, you have now seen that there are various types of distortion which are possible.

What we need to understand here is that, all of these distortions whether it is static or dynamic, circumferential or radial, the basic effect of these non-uniformities or distortion is in the fact that, it affects the engine performance; it affects the engine operation or compressor operation. And therefore, it is necessary that we understand to quantify these distortions. And, also take measures to ensure that distortions, how we can take measures and ensure that the engine can be made more and more tolerant to distortions. So, what we will do next is that we will kind of define a certain parameter, which we will use as a kind of parameter which can quantify distortion saying that, this is the level of distortion that this particular intake is delivering and so on.

So, we will also be defining certain quantification parameter. There are different ways of defining it. We will probably take a look at only one of them, which is more commonly used than the other parameters. Now before that, let us also look at why distortion causes onset of instability. We will look at that in couple of examples. One of them is called a Parallel Compressor theory. We will take a look at that shortly. So, distortion or increased levels of distortion can initiate instabilities, which could lead to either rotating stall mode of instability or you could have a surge itself, which is an axial symmetric, extreme level of instability. So, inlet distortion; basically, what happens in an inlet distortion as we have I just mentioned, it is that we are looking at total pressure non-uniformity, which means that in distorted sector in a region where the flow is non-uniform you could have local flow angles, which are quite different from the design flow angle. That is, certain blades which were happen to fall in the distorted sector will see incidence angles, which are very different from the design incidence angles.

And therefore, some of these, one or more of these blades; because incidence angles are much different from what it is designed for, might kind of undergo stall. And, once these blades undergo stall, it can initiate rotating stall and eventually, it could lead to surges. As well and in some extreme cases of distortion, the compressor might enter into surge even without actually going through this process of rotating stall.

(Refer Slide Time: 21:04)



So, what we see is that, if flow distortion which basically might cause, which basically causes local change in incidence angles. And, when these angle exceed the critical angles; one or more adjacent blades, which fall in this zone of this distorted region would stall. And, the stall cells obviously will propagate, and if they are able to withstand the system dynamics, then the propagated become stronger. If they not; if the system dynamics prevail, then the stall cells will diminish and it will dissipate and does not undergo any instabilities.

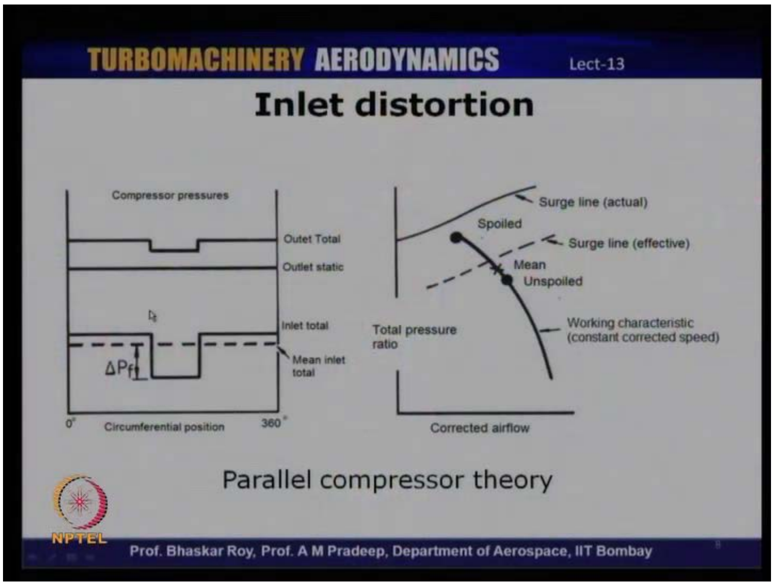
But, in most of the case, that is to when the level of distortion is very mild. In which case, the system dynamics can withstand these distortion levels and does not really undergo stall. In most of the cases, if the distortion levels are higher, then obviously it will overcome the system dynamics and a compressor might encounter surge or stall.

Which is why I mentioned that, all engine manufacturers will tell what the level of distortion is; which this engine can withstand. And, up to that level of distortion, the system dynamics are likely to prevail over the inflow, non-uniformities or distortions. And therefore, the compressor may not really encounter these instabilities. Let me now talk about, as I mentioned certain theory, which talks about how we can explain distortion and its effect in a very fundamental simplified manner. Lot of assumptions, of course are made here. And, it is a rather old theory and, but it is still kind of can explain the effect of distortion in a rather simplified manner.

So, this is basically known as a Parallel Compressor theory. So, as the name suggests we are going to assume the presence of two different compressors, which will basically be an outcome of our discussion here, as well. So, here we are going to talk about the effect of a pure circumferential distortion on the compressor performance. And, here we are going to assume that the circumferential distortion in the simplest form occurs like a square wave. That is, you can approximate the circumferential distorted sector using a square wave signal. So, once such a square wave interacts with a compressor, what happens to it is performance?

So, let us take a look at what happens in such an idealized scenario.

(Refer Slide Time: 23:38)



So, I am talking about Parallel Compressor theory. So, Parallel Compressor theory here, is basically involves assuming a square wave of distortion as you can see here. This is the distortion and the inlet flow, total pressure and so you can see that the inlet total pressure has a square wave jump here. There is a sector where there is a drop, a discrete drop in the total pressure. And, that is on the square wave distortion, we have circumferential. This is the circumferential position from 2 to 360 degrees. So, at some circumferential location you have a square jump or discrete variation or drop in the total pressure. And, so as a result of that of course, the mean inlet total pressure also drops, which should have either, which should actually been equal to this if there was no distortion.

So, similarly you look at the outlet. Basically, we want a compressor to deliver a certain amount of pressure at the exit. So, the outlet static pressure here is assumed to be constant does not really change; outlet total pressure has a certain dip, as well. Now, if we correspondingly look at the compressor characteristic; so here, we have the compressor characteristic in terms of total pressure ratio and the mass flow rate. This one particular corrected speed, which is the working line characteristic.

And, so if you look at the compressor performance, if there was no distortion, the operating point should have been this the one, which is shown by this solid line and referred to as the unspoiled point, which is basically the unspoiled location of operation of the compressor. And, this is the surge line; the actual surge line. Now, because you have a certain drop in compressor pressure in one circumferential location, what basically happens is that this compressor is now trying to develop pressure ratio, well, which is actually higher than what it should have been. Because if you compare the pressure ratio with what it is in the undistorted compressor, the compressor outlet total pressure would have been this. Inlet total pressure is this.

But, now as a result of this drop in inlet flow, in one sector of the inlet flow, the mean inlet total pressure has dropped. And therefore, there is an increase in the pressure ratio; which means that if the compressor was actually operating here, it has now operates it in the spoiled sector or in the spoiled operating condition with a square wave kind of distortion, the compressor is now operating at this point, which corresponds to a spoiled operation.

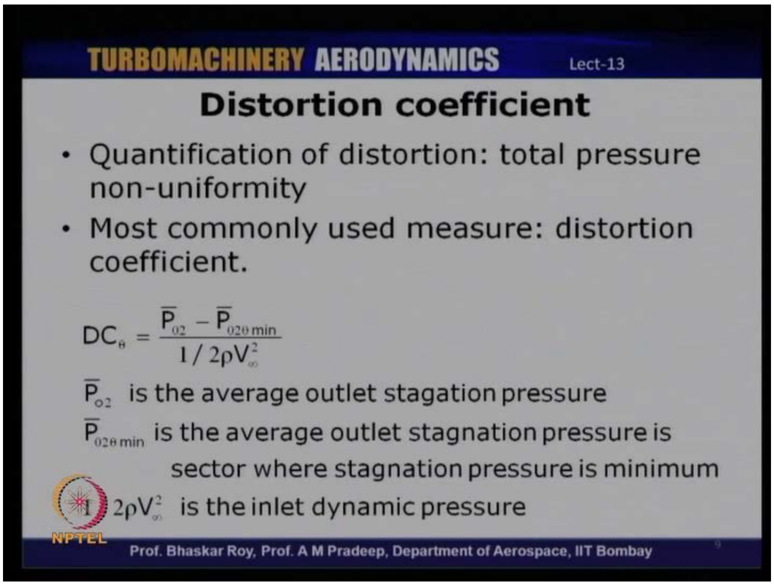
Now, this is a point which is very close to surge line. You can see that, what has basically happened is that the compressor operation has now shifted to another location, which is very close to surge. The other way of looking at it, is that the compressor effectively operation in a distorted sector would shift by a certain amount and at the same time the surge line has shifted downwards. So, you could look at it in either ways. Either that the compressor operation has shifted close to surge or the surge line itself has shifted to a lower location.

Either of these arguments, basically… will tell us that the compressor has now shifted to an operating point, which is closer to surge; which means that if the distorted sector would have been slightly higher, it is likely that the compressor would actually be entering into surge. So, what Parallel Compressor theory tells us in rather simplified manner with lot of assumptions is the fact that, inlet distortion is going to shift the operating point to a point, which is very close to the surge line. We will also be taking a look at an actual compressor operation and the effect of varying levels of distortion, circumferential distortion on the performance.

What we will see is that with the increasing levels of distortion, the surge line shifts towards the right. As it shifts towards the right, basically the operating, well, the surge margin or the difference between the operating line and the surge line starts coming down. That is, there is higher and higher increased levels of threat of surge affecting the compressor performance. So, this is basically an outcome of the Parallel Compressor theory; which in simplified sense tells us how distortion, at least circumferential distortion affects the compressor performance, which is also probably true with the other forms of distortion. We will actually see that, radial distortion is really not that a significant form of distortion because there is always a certain amount of radial distortion, which is present because near the casing and the hub. We always have a growth of boundary layer. So, total pressure distribution is always non-uniform near the casing and the hub. And, so there is always a radial non-uniformity present, even if the flow is undistorted in the classical sense.

So, but circumferential distortion on the other hand, refers to distortion in the circumferential sector. And, that is probably more commonly encountered and more severe and something that we need to understand lot more carefully. So, having understood the so-called Parallel Compressor theory, we will also now try to quantify distortion as I mentioned, right at the beginning. That, we are going to define a parameter, which we can use to kind of quantified distortion and tell us or help us in understanding the extent or the severity of certain amount of distortion. so, this is done using what is known as a distortion coefficient.

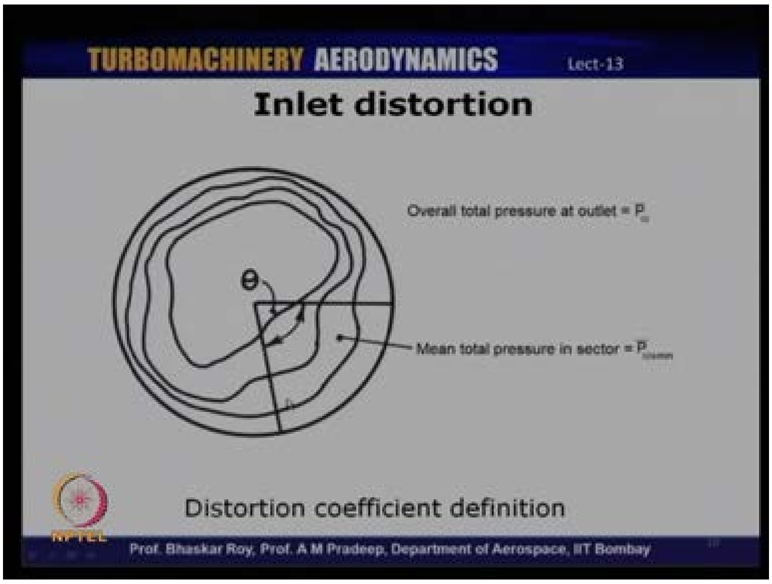
(Refer Slide Time: 30:03)



So, here we are going to quantify distortion only in, as I mentioned in terms of total pressure. We are not really concerned about temperature distortion right now. So, the total pressure non-uniformity is what we are going to quantify.

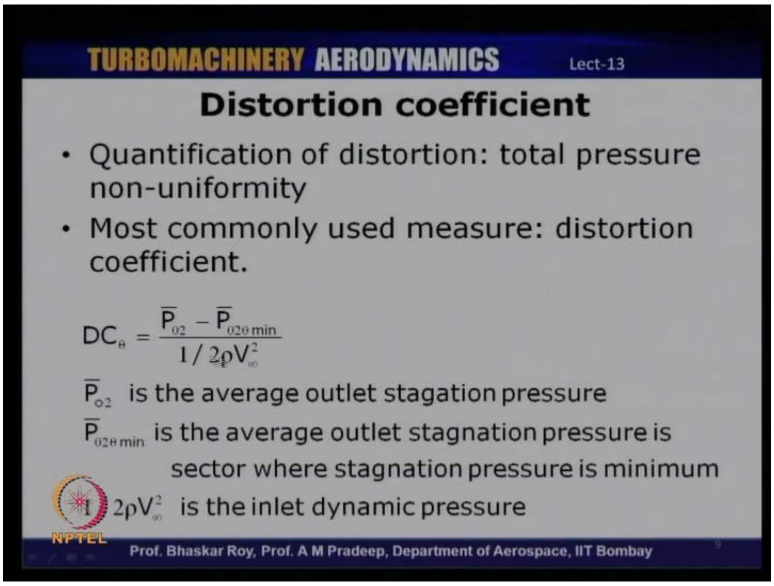
The most common way of quantifying this distortion is using what is known as a distortion coefficient. And, this is usually represented by DC with a subscript theta; where theta is the sector angle, which I will also explain little later. So, DC theta is defined as P 0 2 average minus P 0 2 theta minimum average divided by half rho V infinity square. So, let me explain what these different terms are. P 0 2 is referring to the compressor outlet pressure; average is the average outlet stagnation temperature, stagnation pressure from the compressor; P 0 2 theta minimum refers to the average outlet stagnation pressure in a sector, where the stagnation pressure is minimum. And, of course the denominator is the inlet dynamic pressure let me explain this little bit better using this schematic.

(Refer Slide Time: 31:18)



What is shown here is the compressor inlet phase or the intake or the inlet exit plane, it is also called the Aerodynamic Interface Plane, and these different lines here refer to the total pressure contours. So, if these lines for kind of symmetrical or axial symmetric that refers to a scenario, where there is no distortion. You can clearly see that, here these contours are no longer axial symmetric. That is, they are non-uniform, the maximum non-uniformity being in this sector. So, P 0 2 raise to bar, is basically the average total pressure in the sector. We just take an average; either a mass averaged or an area average. And, P 0 2 theta minimum average refers to average of total pressure in a sector, which is of an angle theta, where the total pressure is minimum. So, which means that, as we scan this whole annulus for different sectors and find the average in all these sectors, the sector where we find that, this average is minimum is what is used here so what distortion coefficient tells us is that what is the extent to which this sector of distortion affects the overall total pressure.

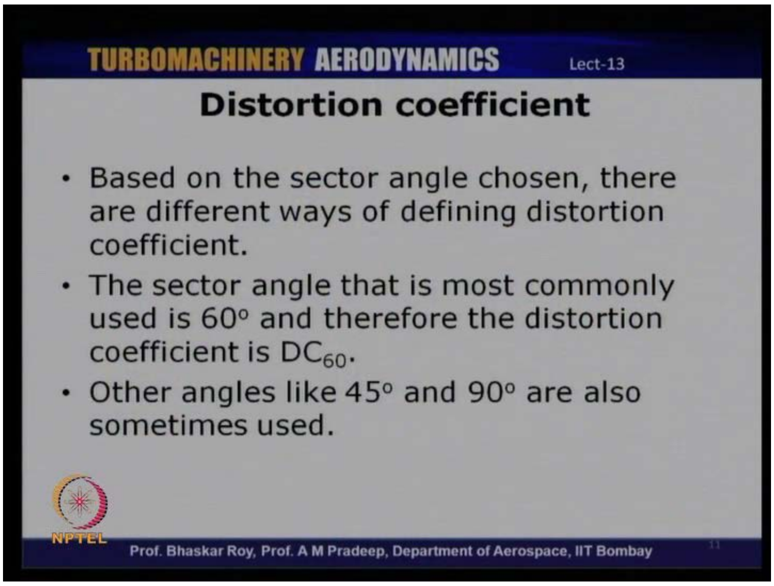
(Refer Slide Time: 32:48)



That is, higher this value of DC theta; it means that the greater is the difference between the average total pressure and the distorted sector. And therefore, greater is the amount of distortion. So, this is one of the ways of defining distortion. And, something which has been very popularly accepted by engine manufacturers and intake designers as a parameter, which can quantify the extent of distortion. There are various other ways in which distortion has been quantified and some of the manufacturers still use them. But, DC theta, DC distortion coefficient is the most commonly adopted parameter, which has been widely used over different industries.

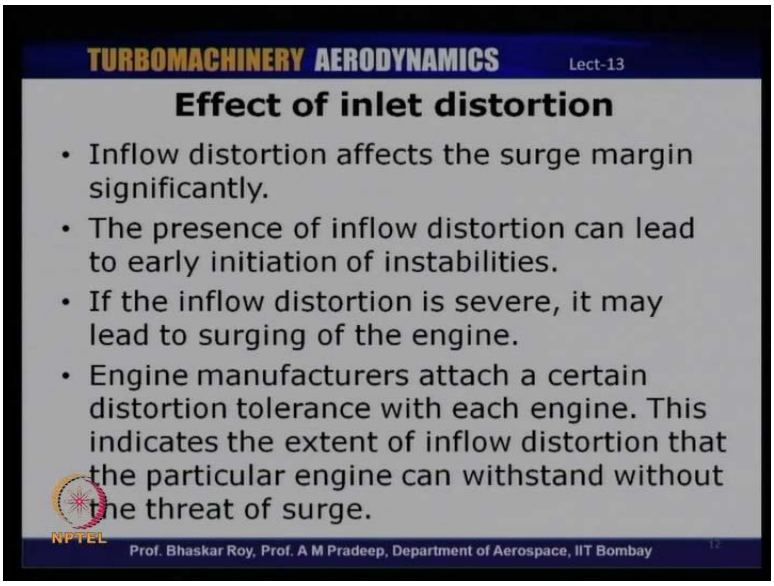
So, the other parameter that we need to look at is, how do we now take this sector angle theta? So, here I just mentioned DC theta; so, you could might wonder, what is the extent to which a sector angle needs to be taken; whether it is 10 degrees or 20, 40, 50, what is the angle that needs to be taken? So, it turns out that the different ways again in which industries and different countries follow the DC theta extent. In most of the countries, they follow or they take a 60 degree sector or in sometimes even 90 degree sectors; so, the extent of distortion in a 60 degree sector and therefore, that distortion coefficient now becomes DC 60. So, DC 60 would be distortion coefficient in a 60 degree sector, which is P 0 2 average at the outlet minus P 0 2 in a 60 degree sector, where average total pressure is minimum divided by half rho V infinity square.

(Refer Slide Time: 34:53)



Similarly, you may have DC 45 or DC 90 and or even 135 and so on. But, DC 60 seems to be the most popularly adopted sector angle which is used. So, other angles like 45 degree, 90 degree are sometimes used. The Russians usually use DC 90; whereas in the west, in the Europe and at the USA they usually take up an angle of 60 degree.

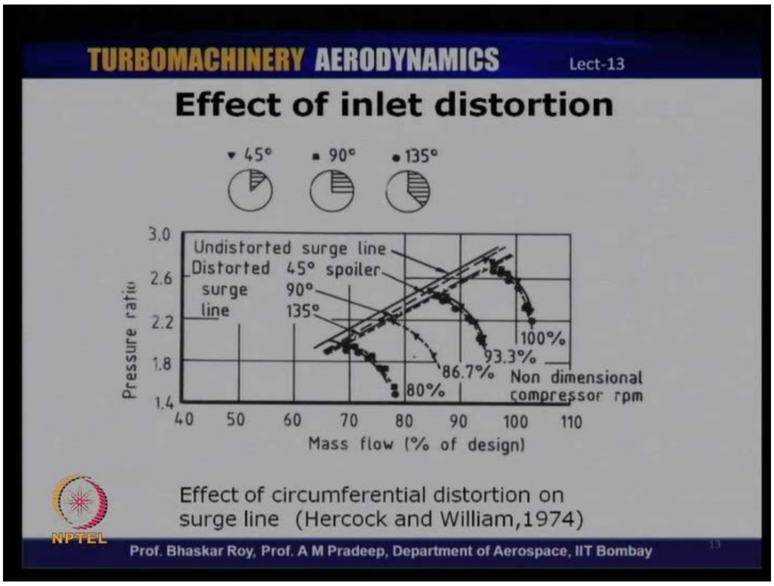
(Refer Slide Time: 35:15)



Now, as we have already talked about effect of distortion on surge margin and basically, what happens is the fact that distortion can lead to earlier initiation of instabilities. And, if these instabilities or distortion level is severe, it might lead to surge. I mentioned that engine manufacturers usually attach a certain parameter or a certain amount of distortion tolerance for each engine. For example, engine manufacturer would say that, this certain engine can withstand DC 60 of let us say 0.2; it means that this engine has been designed to withstand distortion coefficients based on 60 degree sector, DC 60 up to about 0.2.

And, beyond that, if there are instability of with which there are distortion that are coming in from the intake, then the engine can undergo instabilities. And, it cannot really operate efficiently at higher levels of distortions. So, it is necessary that the engine manufacturer passes on this information to the intake designers as well as the airframe manufacturers because they need to know, that this engine can withstand only this much amount of distortion. So, the intake has to be designed or inlet has to be designed to kind of ensure that the distortion levels do not exceed what has been prescribed by the engine manufacturer. So, now, let me give you one example of an actual engine test data, where the engine was artificially subject to different levels of circumferential distortion and how it has affected the engine performance.

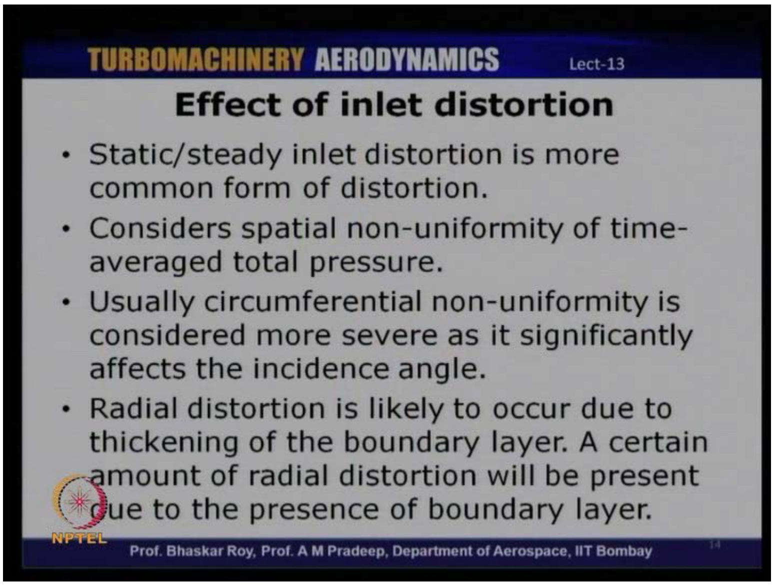
(Refer Slide Time: 37:14)



So, if you look at this performance characteristics that I have shown here, there are three different characteristics shown for three different sectors of distortion, a 45 degree sector and 90 degree sector and a 135 degree sector; which means that in this kind of a test, the engine had an inlet, which had already had a 45 degree sector, which was distorted. Similarly, this had 90 degree of distortion and this has a sector of distortion of 135. So, this solid line that you see is basically the undistorted surge line of this particular engine… This is from a very old test data report published in 1970s, in 1974. And then, you can see that for different speeds as you increase the level of distortion from 45 to 90 to 135, there is a progressive shift in the surge line. This was the undistorted surge line; this is with 45 degree spoiler or distortion 90 degree and 135. So, there is a progressive shift in the surge line as we move from undistorted sector to highly distorted 135 degree sector.

And, this is a very significant aspect that, there is a drastic change or reduction in the surge margin because surge margin would be the difference between the operating line and the surge line. So, higher the level of distortion, the surge margin diminishes and becomes smaller and smaller. And, that is something that is going to be of great concern to the intake designer because he needs to ensure that, the intake can actually deliver a cleaner flow without high levels of distortion. So, if the amount of distortion that is going to affect the amount of the performance of the compressor is known, then the intake designers can probably take some steps into account to ensure that the intake does not really have deliver, rather high levels of distortion to the compressor.

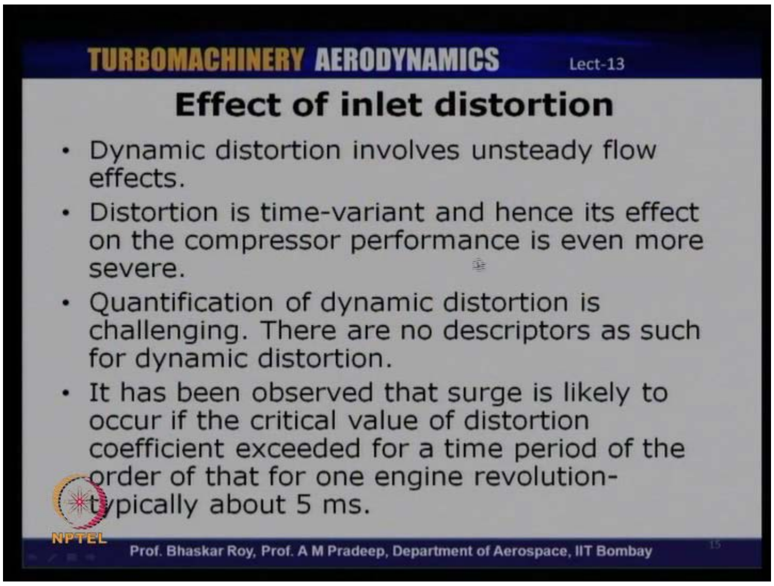
(Refer Slide Time: 39:36)



Now, I mentioned that, the different forms of distortion; there is a static or steady distortion, there is unsteady and radial and circumferential and so on. The static or steady inlet distortion is probably a more common form of distortion, which considers a spatial non-uniformity of basically time-averaged total pressure. Again, circumferential non-uniformity is more severe as I mentioned because it significantly affects the incidence angle. Radial distortion, as I mentioned occurs, even otherwise because there is a boundary layer development at the hub and casing. And therefore, radial distortion will occur even without the intake undergoing an actual distortion. So, radial distortion is something that is going to be there even otherwise.

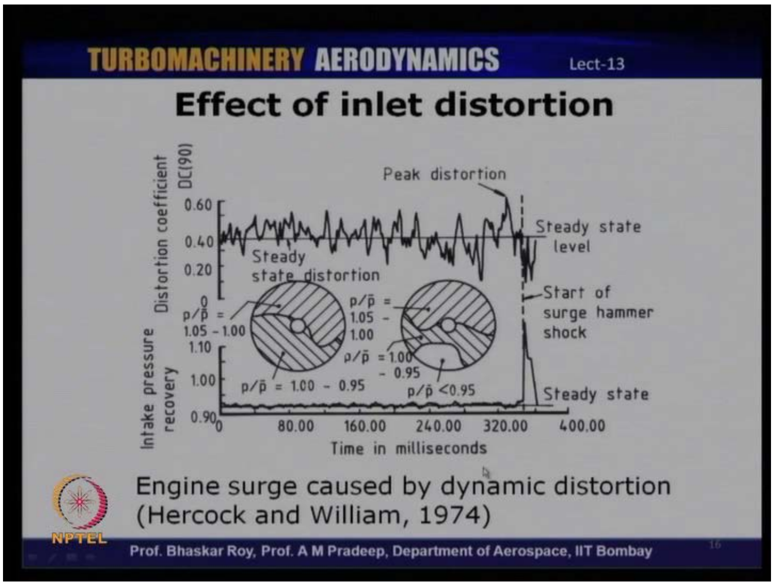
Now, what about dynamic distortion? Dynamic distortion is basically the effect of unsteadiness on a steady distortion. So, if you have a steady distortion and there is certain amount of flow unsteadiness, that can lead to what is known as the dynamic distortion. And, of course dynamic distortion can have far more severe effects on the compressor performance. But, their occurrences are not really that significant; in the sense, that at, then not many instances when you might have a purely, a very high levels of dynamic distortion. Again steady distortion, either said is rather idealized. You may always have certain amount of unsteadiness, but here dynamic distortion refers to very high levels of distortion and it is effect on compressor.

(Refer Slide Time: 41:07)



So, when distortion is time-variant, its effect on compressor performance is even more severe. Then, how do you quantify dynamic distortion? Well, that is quite challenging. There are no real descriptors for dynamic distortion. And, what is observed is that surge is likely to occur, if the critical value of distortion coefficient exceeded for a time period of that of an order of that of one engine revolution that is, typically about 5 milliseconds.

(Refer Slide Time: 41:37)



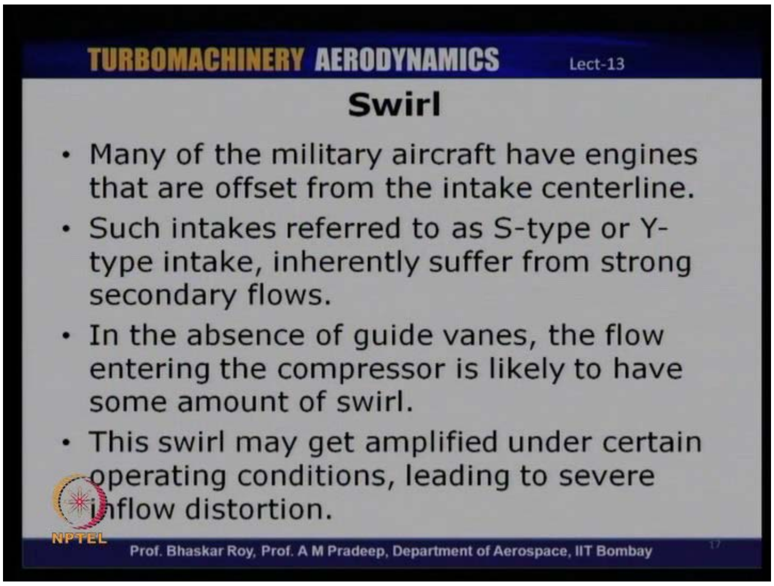
Let me give you one example of this effect of dynamic distortion. This is again from that same report by Her cock and William in 1974. What you see here is the intake pressure recovery as well as the distortion coefficient, here you can see, it is distortion coefficient 90; DC 90, which has been used. And, on x-axis we have time in milliseconds.

So, what you see in both these cases is the change of the distortion, the nature of distortion. In one case we have steady state distortion. So, this you can see the variation of distortion. Average distortion level is about 0.37 of DC 90 and that continues for a certain period of time. But, as the nature of distortion changes, so, this is how it was up to about this point, after which the nature of distortion has changed. You can see that the total pressure distribution has changed. You now have a sector, which is far more distorted than the rest of them. So, that has caused a distortion level to shoot to about 0.6 that is the instant at which it is no longer steady state distortion. It has become unsteady and distortion has now initiated the occurrence of surge. So, here you have initiation of surge as a result of momentary introduction of high level of distortion, which is what you see here locally.

So, there is local introduction of high distortion, which has caused initiation of surge after about a few milliseconds, after this speed distortion was observed. So, this is just to give you an example of how dynamic distortion can very severely and on a very short span of time initiate the occurrence of surge. Even though the steady state distortion was not really initiating surge, the occurrence of dynamic distortion has actually pushed the compressor into the surge in a very short span of time in a few milliseconds. So, that is the amount of effect of distortion that it can have on compressor performance.

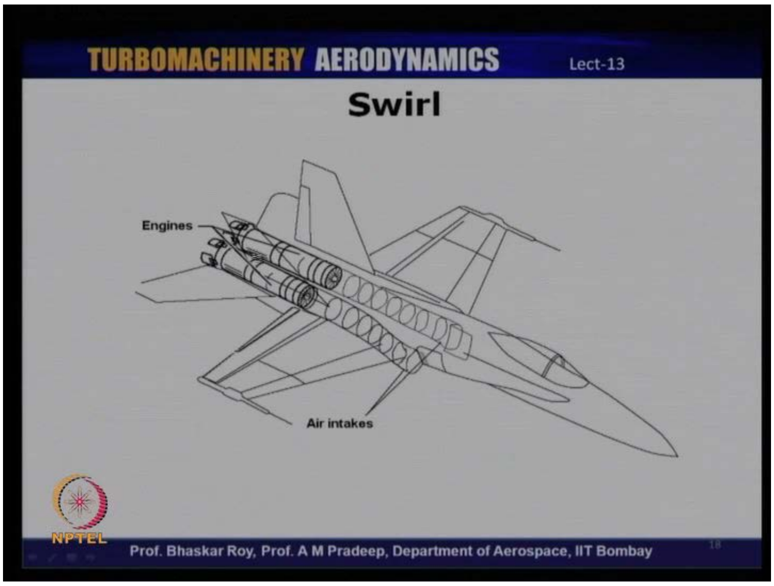
Now, there is another form of distortion that we need to understand well. And, that is to do with swirl. Now, most of the military aircraft as I mentioned, have very highly complicated geometries of the intake. And, such a complicated geometry can itself initiate non-uniformities in the flow. So, the exit flow itself can have lot of secondary flows present, and that can lead to circumferential component in velocity basically referred to as swirl.

(Refer Slide Time: 44:26)



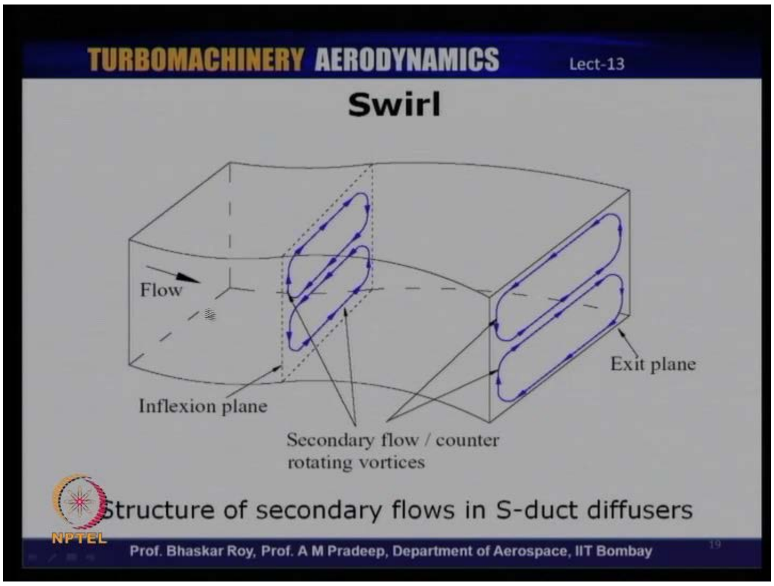
So, swirl is basically a form of distortion. But, it is primarily on account of the geometry itself. So, some such intakes like the S-shaped intake or Y-shaped intake; these intakes inherently suffer from strong secondary flows. And, so in the absence of any guide vanes, the flow entering the compressor is likely to have certain amount of swirl, which might obviously get amplified under different operating conditions, leading to severe inflow distortion.

(Refer Slide Time: 44:53)



So, just to give an example, so, here you have a typical military aircraft, which has two intakes and two engines into which these intakes are feeding airflow. You can see that the intakes have indeed very complex shapes and these are typical S-shaped intakes.

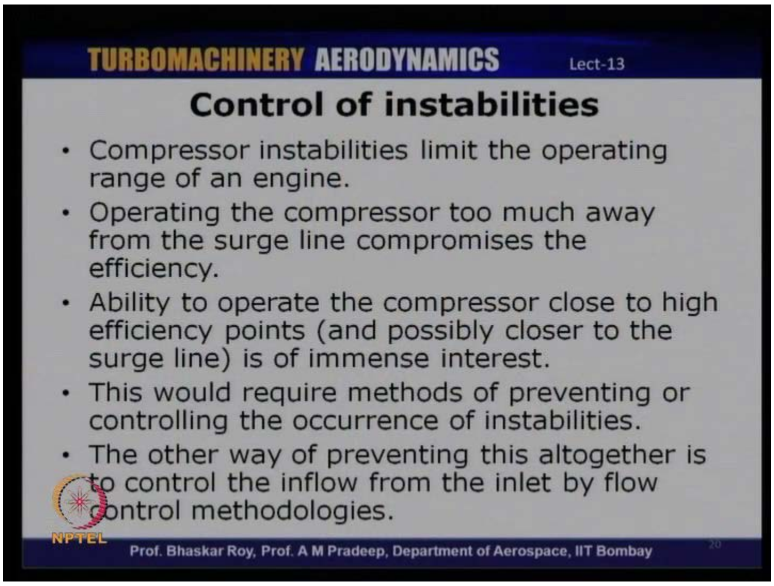
(Refer Slide Time: 45:17)



Since, there geometry itself involves curvatures, such an intake has inherently the occurrence of secondary flows like, what is schematically shown here. So, as the flow encounters curvatures because of difference in pressure gradients on either walls of the intake, you would have secondary flows, which are basically counter rotating vortices leading to swirl at the exit of the intake. And, so this swirl can get amplified under different operating conditions and this can lead to substantial distortion in the exit flow. And, obviously that can affect the compressor performance in a very drastic manner.

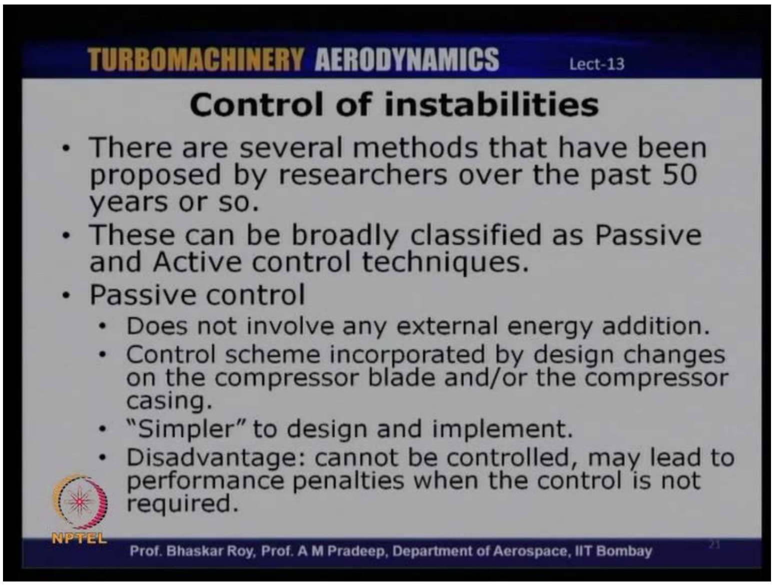
So, swirl is again a form of distortion, and the extent of swirl is basically dependent on the kind of geometry that the intake has, plus, of course the operating conditions which can amplify the amount of swirl and therefore, the amount of distortion. Now, so far we have been talking about different forms of distortion, their effect on compressor performance and so on. So, it is also necessary that we understand the fact that distortion is going to be there, present under extreme operating conditions like in manoeuvers and so on. So, in the presence of distortion and in the event that the compressor is likely to encounter instabilities, are there methods by which in these instabilities can be either delayed or they can be prevented.

(Refer Slide Time: 46:58)



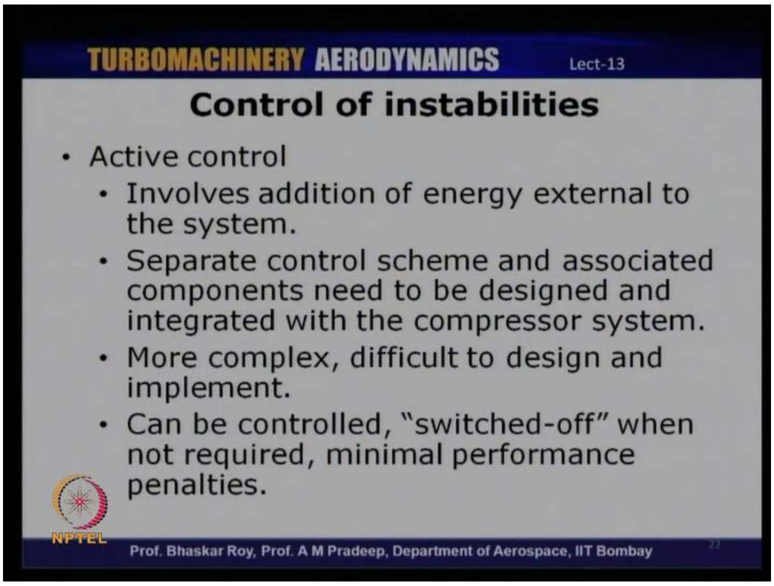
So, what we will talk about in the next few minutes is on different methods of trying to control these instabilities. And, that is very significant in the performance of engines, especially the military engines, which are to operate under very severe operating conditions which are highly off-design. So, ability to operate the compressor very close to the high efficiency points and possibly closer to the surge line is of immense interest to us. Because you would like to operate the compressor at it is highest efficiency point, which means many a times it might be very close to the surge line. So, we would need to therefore, understand methods by which we can operate the compressor very close to surge. But, at the same time we can also extend the onset of surge and instabilities by certain artificial means.

(Refer Slide Time: 47:42)



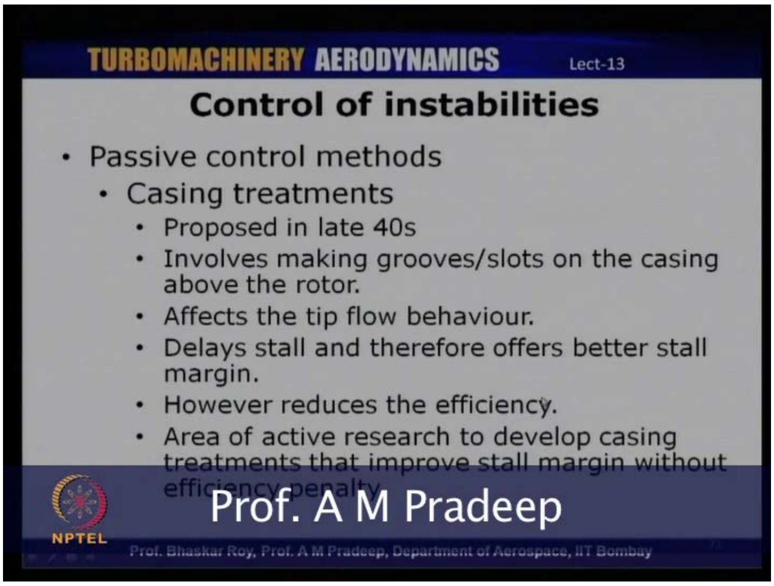
So, there are several methods which have been kind of proposed by researchers in the past fifty years or more. And, these are broadly classified into two groups. They are the passive control techniques and the active control techniques. Passive control techniques are those which do not involve any external energy addition. And, these can be incorporated by design changes on the compressor blade or the compressor casing. And, these are apparently simpler to design and could be simpler in codes because it is simpler in the sense that it is probably simpler than the active control design. But, it is not simple in the absolute sense. And, the major disadvantage of passive control methods are that they cannot be controlled; in, hence that you cannot change the design. You cannot really change the extent of control that these devices have. And therefore, such devices may lead to performance penalties when they are not really required; that is, when the compressor is actually operating under conditions which are nowhere close to instabilities, the presence of these devices themselves may lead to performance penalty.

(Refer Slide Time: 49:03)



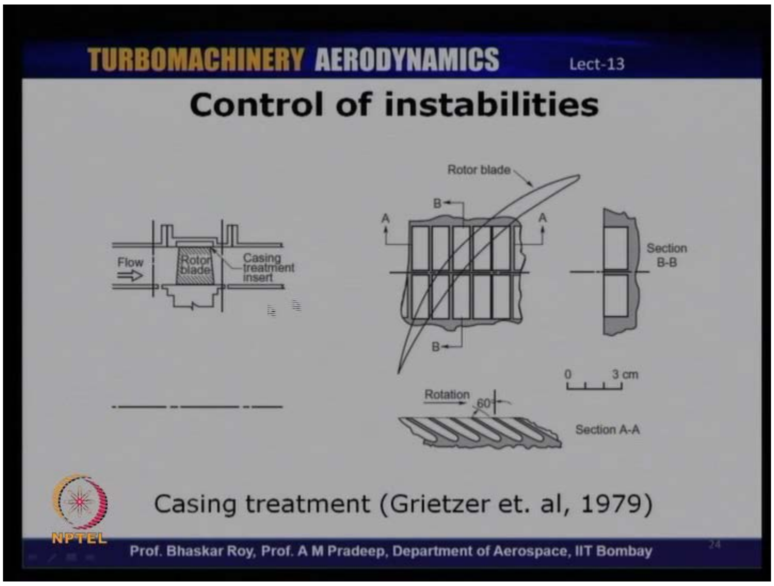
So, we will take up some examples in later slides, which will explain this point. Other set of techniques are known as active control techniques. These are the techniques which require certain amount of external energy addition to the system. And, this is separate control scheme and the associated components need to be designed and integrated with the compressor system. And therefore, these are inherently more complex and difficult to design and implement. But, the advantage is that they can be controlled; which means that, they can be actually be "switched-off" when they are not required. And therefore, they lead to minimal performance penalties.

(Refer Slide Time: 49:32)



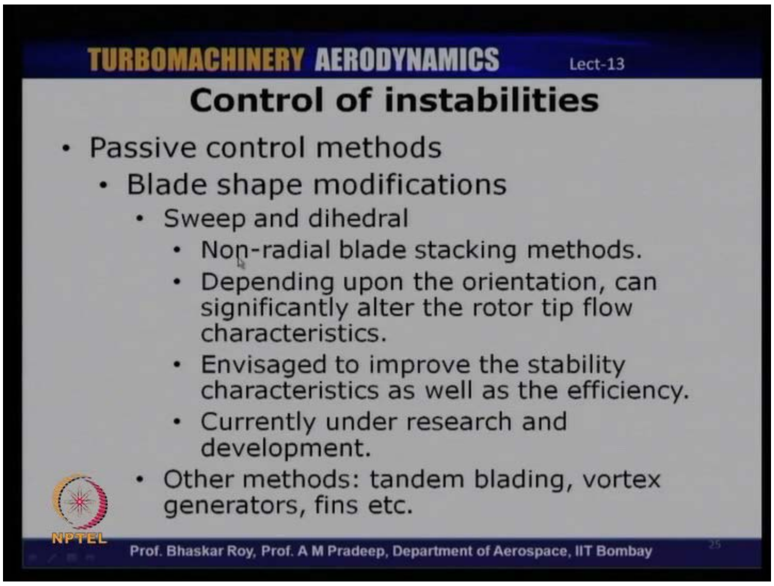
Let us take a look at passive control techniques. One of the most common or widely explored passive control methods is the Casing treatment. These have been, of course around for last fifty years. So, it has been proposed way back in late forties and early fifties. This basically involves making grooves or slots on the casing above the rotor. And, these slots have been designed or to be designed to basically affect the tip flow behavior. So, casing treatments are basically designed to delay stall. Therefore, these methods are supposed to offer better stall margin. But, it has been observed that casing treatments by enlarge leads to reduction in efficiency. And, of course this area of research is still very active and there are continued efforts to develop casing treatments, which are not only beneficial in terms of stall margin, but also in terms of, either better efficiency or no efficiency penalty.

(Refer Slide Time: 50:38)



Just to give an example, what is shown here is a casing treatment study, which was done in late seventies by Grietzer's group in MIT. So, the casing that you see here has been modified by providing grooves. And, you can see that these grooves, if you take a section here, this groove that you see here, are basically referring to the casing treatment above the rotor blade. And, you can see it covers only part of the rotor chord. It does not cover the entire rotor chord. And, such a casing treatment has been found to initiate to delay stall, initiation of stall and therefore, such a rotor configuration was found to have much better stall margin than as compared to geometry without casing treatment. But, of course this came with an efficiency penalty.

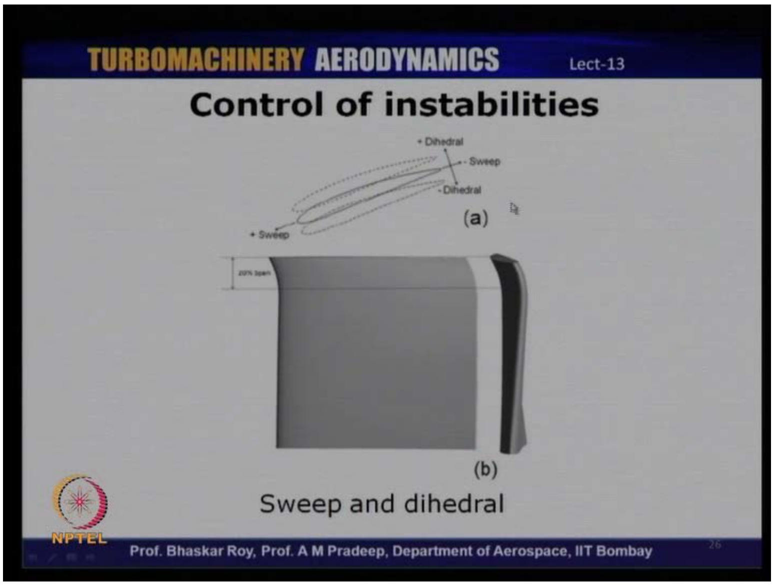
(Refer Slide Time: 51:34)



There are other methods of controlling instabilities, which are again still undergoing lot of research. Some of them involve blade shape modifications like for example, sweep and dihedral, which are basically non-radial stacking methods. And, depending upon the orientation, one can significantly alter the tip flow characteristics. These are primarily envisaged to provide better stability characteristics as well as efficiency. But, of course, these are still currently under research. And, lot of research groups all over the world are working on and trying to develop better methods of providing sweep and dihedral.

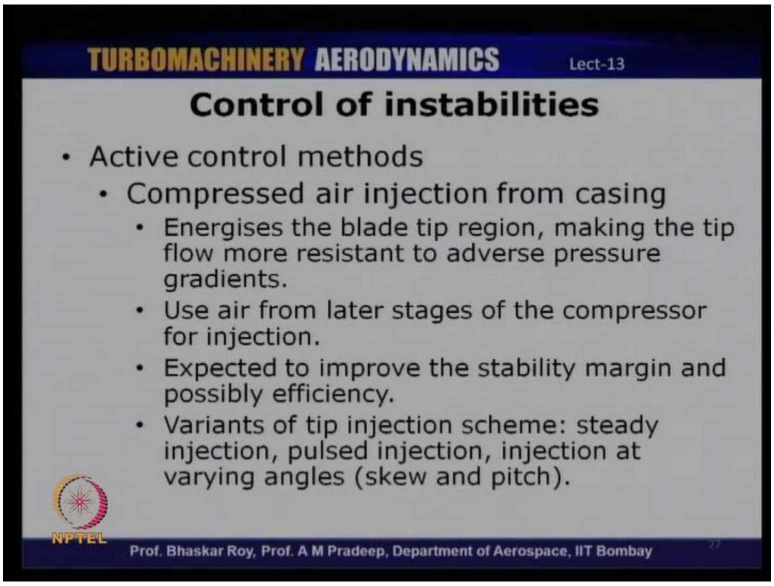
Now, there are also methods, other than let us say sweep and dihedral or casing treatments, which are also passive control in that sense; for example, tandem blade configuration or by using vortex generators and so on. And, so there are several passive control techniques… which are being proposed with. None of these are actually being used in practice, except for some engines, which claim to have some form of casing treatments and so on. But, they are not really been used in majority of the engines.

(Refer Slide Time: 52:45)



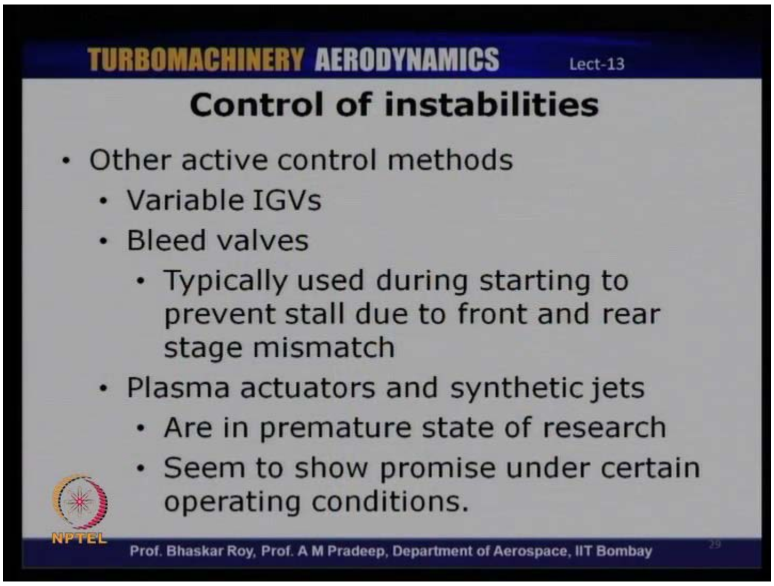
So, this is just an example of what we mean by sweep and dihedral. We will be changing the shape of the blade, either part span or full span by either twisting the blade, providing a certain amount of lean on either sides of the blade or laterally shifting the blade in the case of sweep. And, so these have been found to improve the performance of the compressor and to some extent, also to improve the stall margin of the compressor.

(Refer Slide Time: 53:15)



Now, we now quickly take a look at active control techniques. The most common method of active control has been by energizing the tip region by injecting external air; and therefore, making the tip flow more resistant to pressure gradients. So, it is envisaged that the air from the later stages of the compressor can be used for this injection. And, such a scheme is again expected to improve not only the stability margin, but also the efficiency because it controls the tip flow and the tip leakage vortex in some sense. And therefore, efficiency is also expected to improve. And, there are different variants of this tip injection scheme like steady injection or pulsed injection, and injection at different skew and pitch angles and so on. And, so these are different forms of injection, which are again undergoing lot of studies and researches across. Several groups are currently trying to optimize and develop better ways of energizing the tip flow using active control methods.

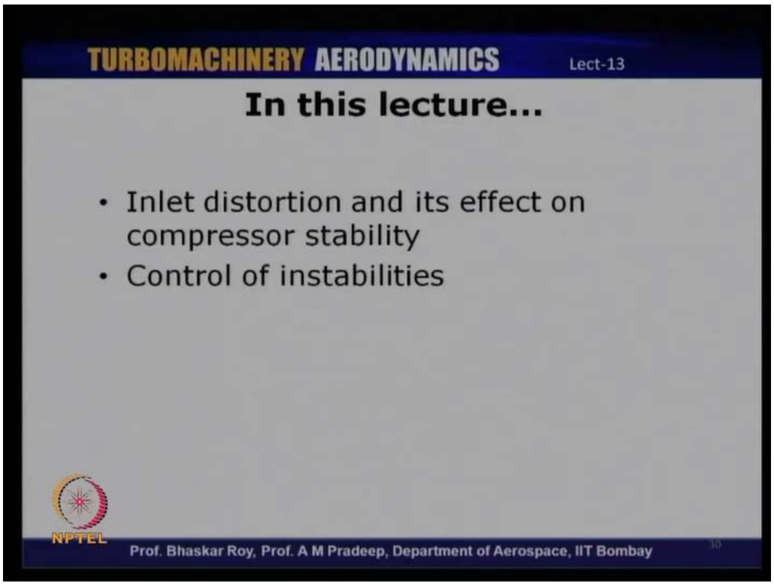
(Refer Slide Time: 54:19)



Besides this, there are other active control methods like variable Inlet Guide Vanes, which can be varied depending upon the inflow conditions. And, bleed valves which are of course, not really active control techniques, but they are typically used during starting of aircraft to prevent mismatch between the front and rear stages. Especially, during starting where there is a severe mismatch between the front stages and rear stages. So, bleed valves are commonly used.

So, it is not really an active control technique, but it does prevent or delay the occurrence of stall, especially during such extreme operating conditions like, during starting. And of course, there are other emerging areas of active control area techniques like plasma actuators and synthetic jets, etcetera. Of course, these are very premature. Currently, the state of research is very premature and, but they see to at least show certain promise under certain operating conditions. So, as you can see, there are varieties of methods which have been proposed over the years, which could be used for delaying the occurrence of instabilities. But, you can see that some of them or many of them in fact, come with a certain amount of efficiency penalty and that something that will need to be worked upon and improved upon. To ensure that, such methods not only improve the stall margin or surge margin, but at the same time it also does not lead to significant penalties in terms of efficiency. And therefore, most of these methods are currently undergoing lot of research. And, it is expected that some of these techniques might get implemented and used in some of the future engines, which could have use of these methods to ensure that the compressor operation is basically very close to the surge, at the same time the presence of these techniques can ensure that the occurrence or initiation of these instabilities can be extended.

(Refer Slide Time: 56:29)



So, let me just recap what we had discussed during today's class. We, primarily been talking about inlet distortion and its effect on compressor performance. So, we spent quite some time in today's lecture talking about distortion, trying to quantify distortion and also the different types of inlet distortion, and how distortion affects the compressor performance in terms of earlier initiation of instabilities, and what effect distortion has in terms of initiation of these instabilities. We also had some discussion on some certain classical theories involved here like the Parallel Compressor theory, which talks about the effect of circumferential distortion on the compressor performance, in a very simplified manner. And, subsequent to that, we also had some quick discussion on the different types of methods or types of control techniques, which have been proposed for control of the instabilities like the active control techniques and the passive control techniques, and what are these methods. We had a very quick discussion on many of these techniques. And, as I mentioned, most of these techniques are currently under development and none of them are really been commonly used in large scale in modern day engines. But, it is expected that some of them would indeed be used in future engines.

So, these were some of the topics that we had discussed in today's class. And, we will continue with discussion on more of these topics in subsequent lectures.