Turbomachinery Aerodynamics

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Lecture No. # 12
Instability in Axial Compressors

Hello and welcome to this lecture, that is, lecture number twelve of this lecture series on turbomachinery aerodynamics. I think in the last several lectures, we have had a chance to interact discuss about several aspects of turbo machine, the term. The thermodynamics associated with turbo machines and a particularly related to axial flow compressors. So, in today's lecture and in the next lecture that would be lecture thirteen, we are going to discuss about very significant aspect, I mean very important aspect which sort of limits the whole operation of the whole engine as a whole, and that is to do with the stability of operation of axial compressors.

So, we are going to talk about compressor stability and different forms of instability that we see in modern day axial compressors, and what are the effects of instability on the compressor performance and also the performance of the engine as the whole, and some of, we will of course, continue discussion on instability in the next lecture, where we will also be talking about the effect of inflow conditions on the initiation of instabilities as well as the effect of trying to control instabilities, and how we can try and control instabilities in axial compressors and what are the implications of this control on the performance of the engine as a whole.

So, instability is the major topic that we are going to discuss in today's talk. So, basically we are going to talk about two different modes of instability. We will of course, we are talking about that in a great detail, that is to do with the rotating stall and surge.

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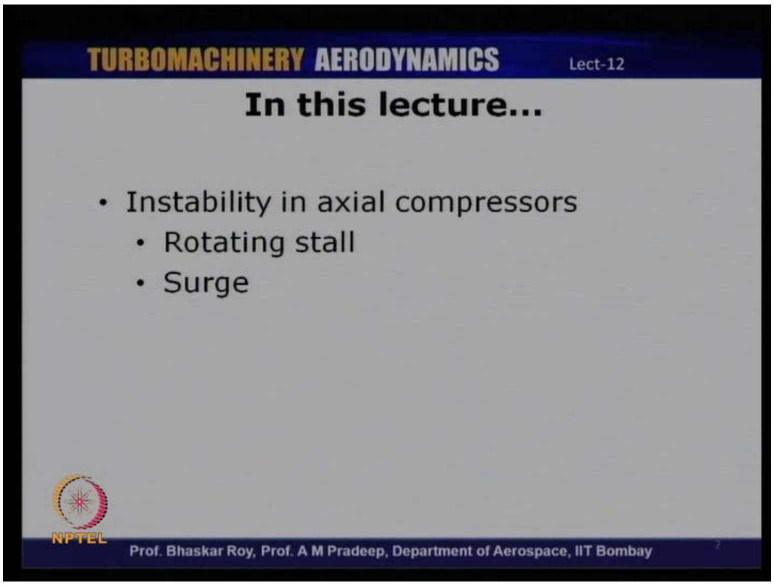

So, these are the two basic aspects of the instability will be talking about; of course, we will cover instability in general as well in today's talk. Now, one of the major issues with the engine operation and, and, the effect of train to operate under of design conditions is the fact that there is one component which will sort of limit the performance or limit the operation of the whole engine as a whole and that is the compressor. So, compressor is the component which sort of determines the stability and limits of operation of the engine as a whole.

Now, in the last class, if you remember in one of the last lectures, we had discussed about the axial flow compressors performance map. During this discussion, I think I had mentioned that there are two limits of operation of the axial compressor. On the right hand side of the compressor map, we have what is known as this choking point or the chock limit, which is to do with maximum mass flow rate, and on the left hand side of the compressor map, we have what is known as the surge limit or the surge margin or the limit to which the surge can occur. So, these are the two bands or regions or lines within which the compressor operation is considered stable or feasible.

So, if you try to operate the compressor beyond these limits, the compressor is going to go in to instability modes and the operation cannot be successfully carried out, and therefore, what we also see is that, if you look at the engine as a whole, compressor been one of the major components of the major components of the engine. If the compressor enters into a instability mode, obviously, that is going to have a detrimental effect on the down string components like the combustion chamber. Therefore, the turbine and nozzle and their and so on.

So, the stability limits of the compressor will kind of limit the operation of the whole engine, and that is why it is very important that we understand what are the different modes of instability and how we can sort of understand the mechanism of these instabilities and see what initiates these instabilities, and of course, in subsequent lectures, we will also look at how we can attempt to control these instabilities if at all possible. So, compressor instability or the limits of operation of the engine is limited by the operation or the range of the operation of the compressor itself.

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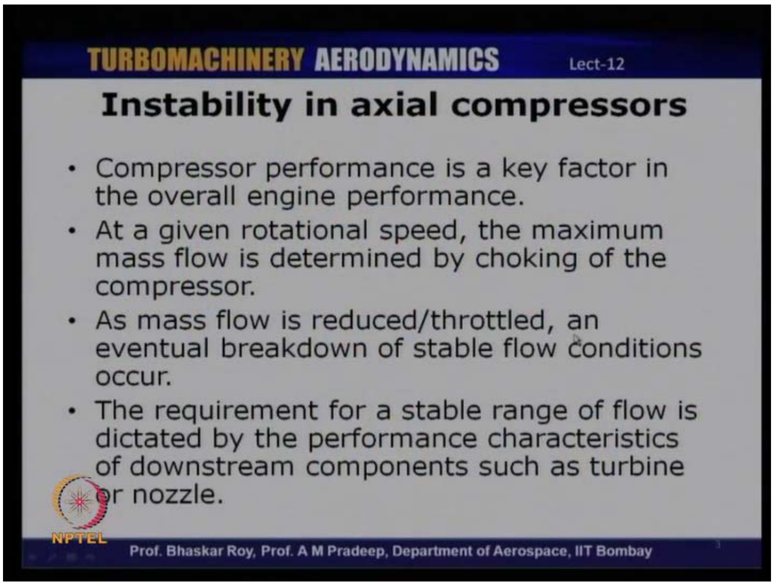

So, let us take a look at some of these salient features. As I mentioned, compressor performance; obviously, is a key factor in the overall engine performance. At a given rotational speed, we know that the maximum mass flow is determined by the chocking, and as mass flow is throttled, there is an eventual breakdown of the stable flow conditions and the stable performance or range of the engine is therefore dictated by the compressor performance itself, and what we also like to understand here is the fact that, the an aero craft engine as we know is designed to operate for a certain condition which is known as the design condition, but during takeoff to climb and cruise and finally, to land, we see that the engine is operating under variety of operating conditions.

So, how is it that we can kind of ensure that this engine is going to operate stably in all these operating conditions? Now, that is a big challenge for an engineer, for an engine designer because there are so many components that fit into a an aircraft engine, and how do you ensure that each of these components will be able to perform well under all these called of design conditions, and one of the most crucial components amongst all the other components is the compressor, because compressor performance as I mentioned is limited between the chock limit and the surge limit, and there is a certain band which we can use for a stable operation of the compressor and we do not want the compressor to operate at towards the these two limits or very close these limits because you know that will risk the compressor in the event of an off design operation that it might go into the instability modes.

Therefore, there is a narrow margin of a operation of the compressor which is known as the surge margin. We will discuss that little later as well. That is the band of operation around the design point where we can say that the compressor operation is stable and compressor is operating a fairly high level of efficiency because that is another important aspect that you might still able to operate a compressor at any other given point, but then, that could be an operating line where the or operating point where the efficiency is very poor, and so, poor efficiency of the compressor will also affect or impact the overall efficiency of the engine. You do not want or an engine designer would never want that in the engine is operating in a poor efficiency zone.

So, high efficiency is one of the key parameters and so is the stability of the compressor itself, and surge margin is that margin which engine designer provides or a compressor designer provides so that the engine can operate in that margin in a stable manner and also with a reasonably high level of efficiency which is also very crucial for the performance of the engine as a whole.

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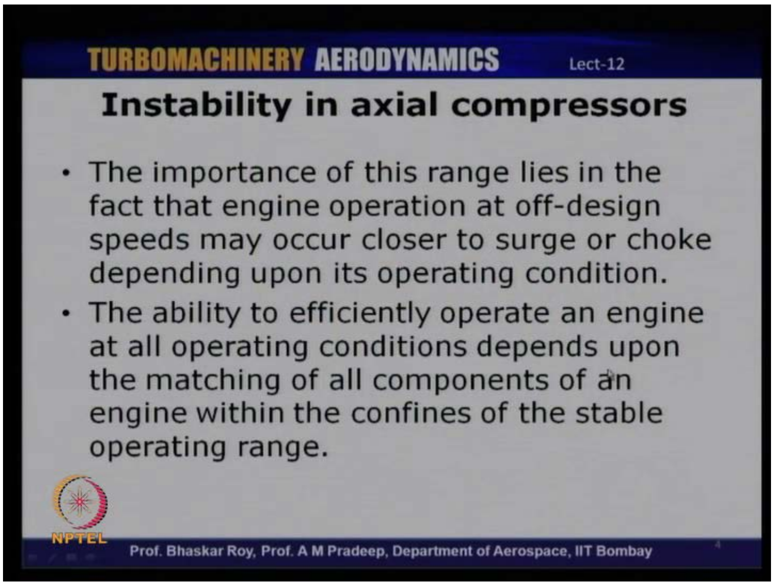

And so, the ability to efficiently operate such an engine at all these operating conditions will also depend upon a successful match of all the components within an engine and also within the stable operating range. So, for example, an engine has, as you has you probably aware and it will typically an air intake, then a fan or a compressor, then the combustion chamber, turbine and a nozzle.

So, there are, these are of course the salient features of a so called turbo jet engine, and so, all these components need to operate in a kind of a synergistic manner in the given operating the range as well as under of design conditions which are expected that, which are expected to be encountered by the engine and compressor being the key component in all of them. It is very necessary that the engine designer understands the performance of the compressor over a range of these operating conditions.

So, what I will do now is to quickly go through the compressor map once again, you have discussed that in one of the earlier lectures. Let us quick take a quick look at that once again, and we will also try to see or try to understand what I am currently talking about; what are these different limits that I have been talking about.

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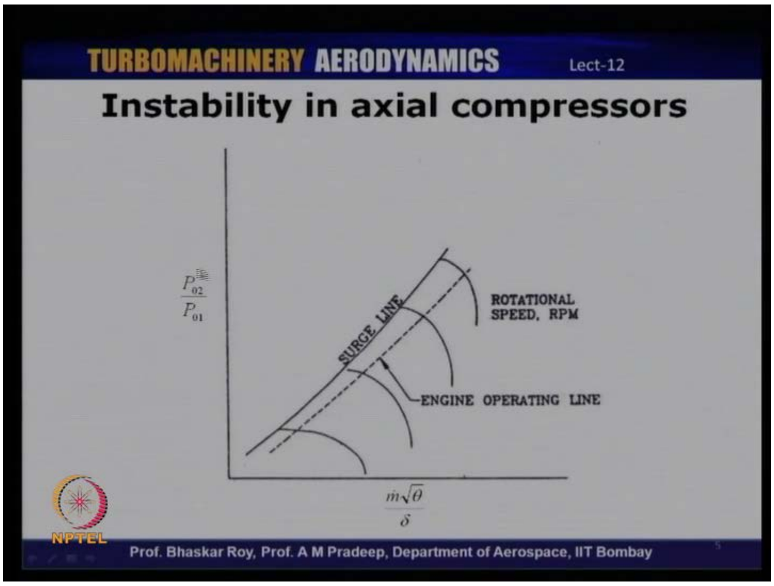

So, here is a typical compressor map, a typical multistage compressor map. On the y axis we have the pressure ratio and x axis is the corrected mass flow rate, mass flow rate m dot square root of theta by delta, where this is the temperature ratio and this is the normalized pressure ratio. So, a typical compressor map will consist of these lines which correspond to different speeds. So, rotational speed is given by these different lines and we have seen two different limits that I was talking about - one is about chocking, that is, this line here. If you draw a line here that corresponds to the chocking limit, because you can see that here beyond this point, the mass flow rate does not change and that for a particular speed, there is, that is the choking limit. On the left hand side, we have a line which I have denoted here as surge line. We will talk about surge in lot more detail in some of the earlier later slides.

This is the surge line compressor operation on the left hand side of this line is unstable because of occurrence of surge, and what is shown here by the dotted line is the engine operating line. Now, engine operating line now engine operating line is the line which the designer has set for a stable operation for the engine at different speeds and the difference between this and the surge line is the surge margin.

So, you can see that it is a other narrow margin been slightly exaggerated here. Modern engines the surge margins are kept very narrow because the higher efficiency is obtained very close to surge, and so, surge margin is this difference that you see here. So, this is a typical compressor map and this is going to limit the performance of an engine as a whole because you have so many components, other components other component s in an engine, the turbine, the combustion chamber, the nozzle intake and so on, and. So, compressor map will tell us what is the kind of limit that we have for operating this engine in a stable manner. So, in the operating line that you saw, that is basically corresponding to the line or zone which has been design by an engineer for a stable operator of the engine. The engine is still allowed to deviate from this operating line by certain amount, but certainly not beyond the surge margin because that would mean that the compressor has surge and that would also mean that the engine operation is in danger. So, we will discuss about surge a little later.

So, the basic intent of this lecture is to understand what are these different instability modes that are likely to be encountered by a compressor and what is the mechanism of these instabilities and what happens really doing these instabilities, but before that, let us first try to understand what we mean by instability in the first place. Let us try to understand or will let us try to define instability, and from there, we will talk about instability as applied to a compressor.

Now, we have, if you have undergone certain courses in physics and equilibrium and so on, you probably are familiar with stability or instability as a general term. So, we are, we are, referring to that in this context also in that fashion. Basically what we refer to as stability of a compressor is the fact that, if a compressor or if a system is perturbed or disturbed from its equilibrium position, if the perturbation or disturbance is removed and the system returns to its initial or original state. Then we refer to the system to be a stable system.

That is exactly what we talk about and we and we talk about compressor as well that, if the compressor operation is perturbed by some downstream condition like a throttling of the nozzle or something like that, then if that perturbation cause of course, that will lead to certain change in compressor operation. Now, once that perturbation is removed, if the compressor returns to its original state, then we say that the compressor operation is stable, and if it does not return to its original state and if the compressor operation enters into an entirely different mode with all kinds of problems, then we refer to this state of operation as an unstable or instable mode of operation of the compressor. We refer to this operation is that instability has set in into this compressor operation.

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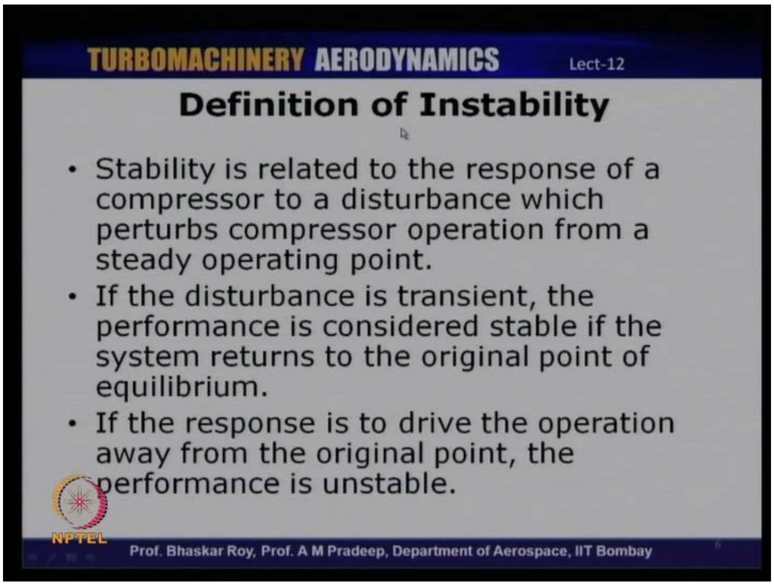

So, stability what in the, in this context of a compressor is basically related to the response of a compressor to a disturbance which perturbs the compressor operation from a steady operating point, and if the disturbance is transient, the performance will be considered stable if the system returns to its original state of equilibrium. If the response is to drive the operation away from the operating or original point, then the operation or performance is unstable.

So, the compressor could depending upon its mode; it could operate in either of these redeems; it could either return to its original state where we say that the compressor is indeed stable, or it could also happen that the compressor does not return to its original state and that is referred to a unstable mode of operation of the compressor. So, these are the different ratios that we are going to discuss in today’s talk. What are these unstable or modes of instabilities that a compressor is likely to encounter. So, let us now talk about the different types of instabilities that a compressor will encounter. We can classify instabilities encountered by a compressor into broadly into two types - one is known as an operational instability and the other is known as aerodynamic instability.

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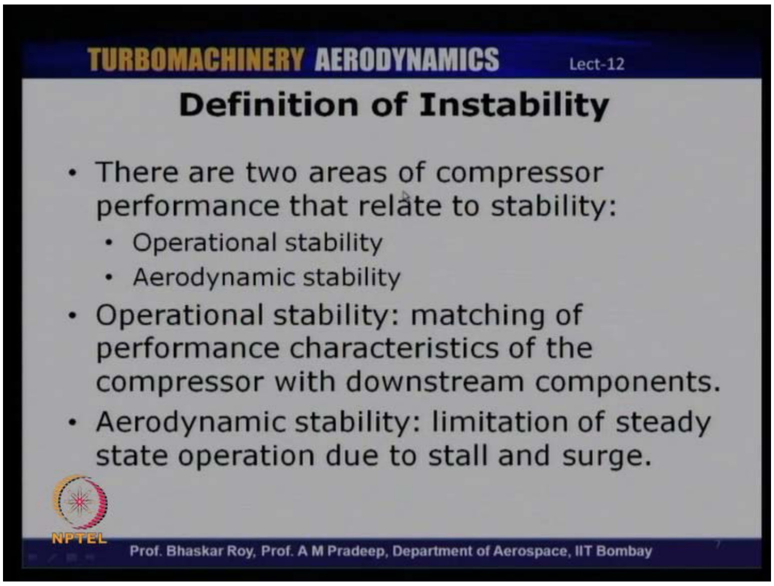

So, there are two areas of compressor performance that related to stability - basically one is to do with operational stability; other is aerodynamic stability. Now, operational stability involves matching the performance characteristics of the compressor with the downstream components. Aerodynamic stability is the limitation of steady operation of the compressor due to what are known as surge and stall. So, we will spend lot of time discussing about the aerodynamic stability because this course is primarily dedicated to aerodynamics of compressors and turbines and other turbo machines.

So, but let us also try to understand operational stability as well. Now, operational stability as we have just seen relates to relates the compressor to certain downstream components as well, that is, if the downstream components kind of perturb the compressor operation, what happens to the overall operation of the compressor and so on.

So, that mode of stability is basically referred to as the operational stability, and here, we consider not just the compressor, we consider components which are also kind of dependent on the compressor or components which kind of influence the compressor performance as well, and what are these different components? It could be downstream components like the combusting, chamber the turbine the nozzle and so on. So, these are the components which can kind of influence the compressor performance. So, operational stability will also take into account all these components put together and their effect on the compressor performance.

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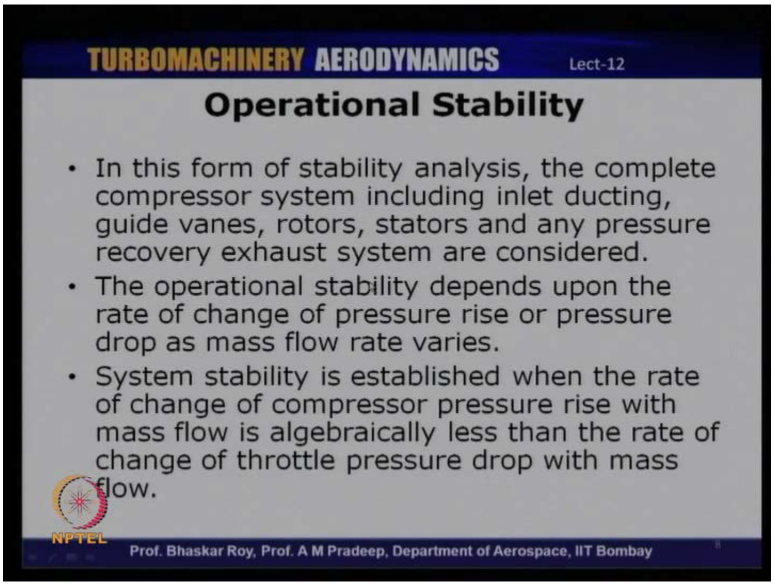

So, in operational stability, the complete compressor system including the inlet ducts, guide winds, the rotor stators of the compressor and the exhaust systems are considered, and operational stability basically depends upon the rate of change of pressure rise or pressure drop as the mass of the rate varies. System stability is established when the rate of change of compressor pressure rise with mass flow is algebraically less than the rate of change of throttle pressure drop with mass flow.

Well the last statement looks a little confusing. I will, I will, try into explain that in, in, one of the next slides which I will talk about, where I will try to explain what I mean by this last statement saying that the stability is established when the rate of change of compressor pressure rise with mass flow is algebraically greater than the sum of the, less than the sum of that of the throttle mass flow. So, let us try to understand this in little more detail. Now, for that, we will again take a look at compressor map at very schematic of a typical compressor map. We will try to look at what we mean by this particular statement; how we can analyze operational stability of a compressor.

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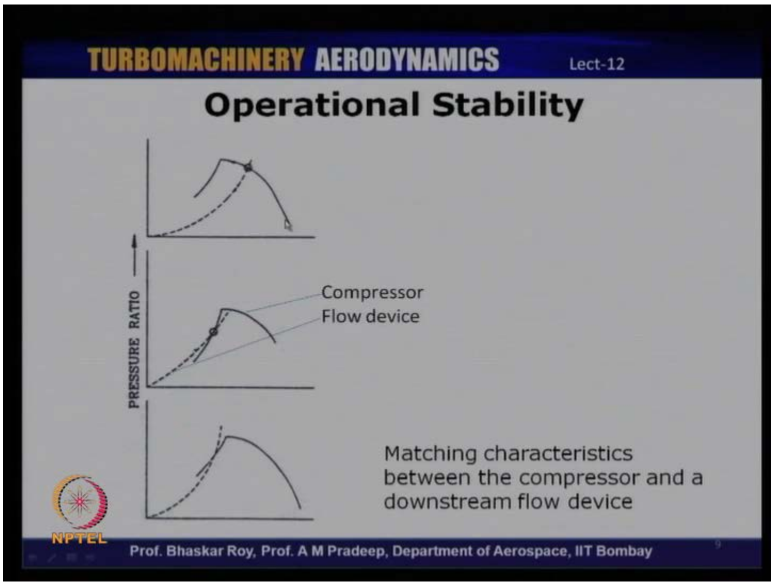

So, I have here a typical line, operating line of the compressor speed line. What is denoted here by the dotted line refers to the characteristics of a throttling device or a flow device it could be a nozzle or it could be some other component which is downstream of a compressor and that can change the compressor operation. So, solid line refers to the compressor operation; this line refers to a throttling operation. So, there are three different modes of operation I have shown here. Let us take a look at the first one. Here we have the compressor characteristic shown by this line and the throttling characteristic shown by this.

So, the throttling characteristic intersects the compressor characteristics at this point which is denoted here. Now, according to what we had discussed in the last class as well as in the earlier slides, this line which is shown here should be an operating, a stable operating line. Any point here should be stable and any point to the left of this should be unstable. Let us take a look at why that is true. So, if you look at this line of intersection, a point of intersection here, that is lying on a region where the compressor operating or compressor map has a negative slope.

Now, when the slope is negative, it means that as the throttling device is operated. Let us say you increase the throttling pressure. With an increase in throttling pressure, it leads to or the, with an increase in throttle, basically means that the mass flow is reduced. So, as the mass flow is reduced, what happens here is that there is a corresponding increase in the pressure rise across the compressor, and therefore, that corresponds to a region where the operation should be stable because your throttling it the pressure is increasing and therefore, that is what exactly should be happening.

Now, let us take a look at the second plot here. The second one shown here where the throttling characteristic intersects the compressor line on this curve here, on the left hand side of the surge line and that is the intersection point here. So, here, what we see is that the slope of the throttling line is less than the slope of the compressor line, compressor operation. So, compressor characteristic has a steeper slope than the throttling characteristic.

So, this means that since the slopes are different here the rate, let us say we consider the rate of change of throttling mass flow rate of change of throttle and we compare that with the rate of change of compressor characteristic. So, as your throttling characteristics are changed, rate of change of, that is now less than the rate of change of the pressure drop across the compressor, which means that as you throttle more and more, the pressure drop across the compressor is less than what it should have been.

And therefore, what will happen is since the pressure drop is low, it will lead to a scenario where the since the throttling mass flow, rate of change of throttle mass flow is larger. It will lead to further decrease in mass flow and so on the, an and the again since the slope of the compressor is still higher, it could lead to further decrease in pressure ratio and this goes back and forth. So, you can clearly see here that, if the throttling characteristics has a slope which is less than that of the compressor characteristic, then that is a region where the compressor operation is going into an unstable mode of operation. So, this is a typical example of an operational instability.

Now, the other extreme of this is something that is theoretically possible, but we will see that aerodynamically that is something that cannot be really achieved. That is the third characteristic that we have here where the compressor characteristic has a slope which is less than that of the throttle characteristic. So, there is a difference in the slope between the compressor and the throttle, and what causes that, I mean what happens in such a scenario. So, if the throttle line has a slope which is greater than the compressor slope itself, what it means is that, as you increase the rate of change of or as the rate of change of throttle is varied.

The corresponding pressure ratio or drop in pressure ratio is lower than that of the corresponding rate of change of mass flow, and therefore, what happens is as the mass flow is changed here since that rate higher than the rate of change of pressure drop, then it means that the pressure drop does not fall at the same rate as that of the mass flow, and therefore, this could lead to us, at least a theoretically could lead to a stable operation of the compressor, which means that we are not really in an unstable mode here. Even though we are operating on the left hand side of this line which is theoretically suppose to be an unstable zone of operation, but what the c is that, it is in fact theoretically possible that we can still operate, we can still have an operational stability even while operating on the left hand side of the performance curve and

So, theoretically it should be possible for us to operate on that side, but what we will see next is that, that is the region were aerodynamic stability cannot be achieved and that is what the next topic that we are going to talk about, that is, to do with aerodynamic stability of an axial compressor, and that is something of more, little more significance to us because we are talking about aerodynamics of compressors right now and. So, understanding aerodynamics stability probably will be of little more significance to us.

So, what do we mean by aerodynamic stability? Now, aerodynamic stability basically refers to the compressor system and its ability to maintain or deliver a higher or increase in pressure rise even when there is a perturbation in the mass flow to a lower value, that is, as you perturb the mass flow to a lower mass flow, ability of the compression, ability of the compression system to either maintain the pressure itself or increase the pressure for a lower mass flow, which just what happens if you remember on a compressor curve, as you keep going from the chock limit to the peak pressure, as you decrease mass flow here, actually getting a better higher and higher pressure ratio, up to the peak pressure point where this slope is kind of 0. Beyond that to the left hand side is where a drop in pressure drop in mass flow will also lead to corresponding drop in pressure ratio, which is not obviously a desirable characteristic because it leads to aerodynamic instability.

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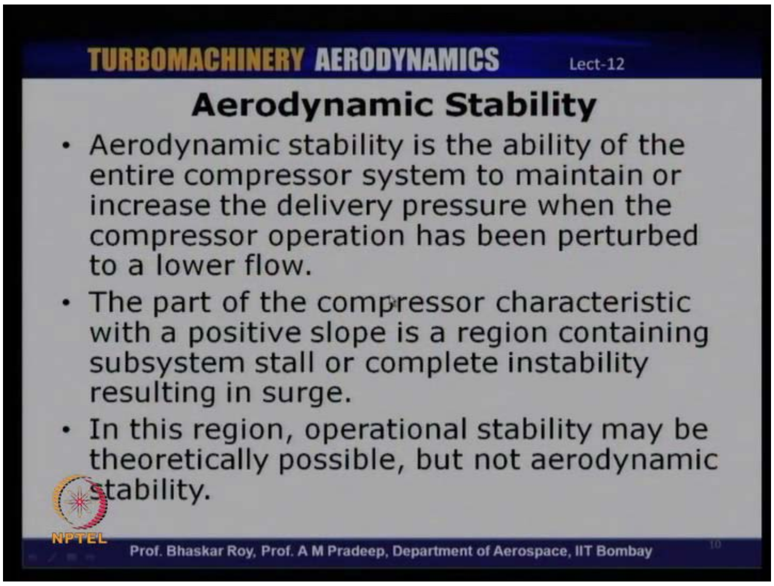

So, this part of the compressor characteristic which has a positive slope is a region containing subsystems stall or complete instability which could lead to surge. So, stall and surge are those two instabilities which we will get initiated if you are to operate on the left hand side of the curve. So, in this region as we have seen, operational stability may still be possible, but aerodynamic stability is not possible.

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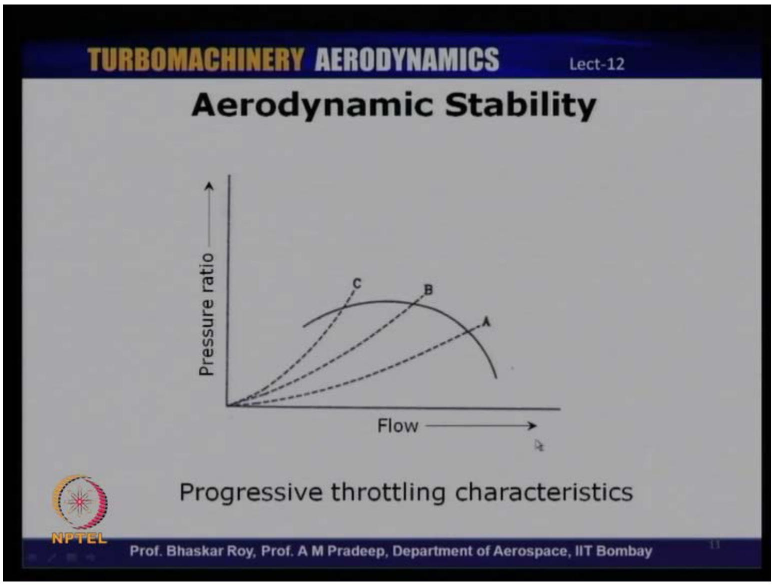

So, let me explain that little better. So, this is a typical compressor characteristics because its rather flat curve as compared to what actually happens in compressors where you could have a sudden drop in certain conditions. Now, here, the dotted lines indicate throttling characteristics as we have seen in the last picture as well there are three different characteristic shown here given by A, B and C. These are three different throttling characteristics and the solid line corresponds to the compressor characteristic itself.

So, between points A and B or between these lines throttling characteristics of A and B as we have seen, these characteristics intersect the compressor characteristics where the compressor, the slope of the compressor performance is negative. Therefore, these lines correspond to stable operation of the compressor itself. Now, here, what we have is that the, let us consider let us say point A. Now, here, we have an increase or between point A and B. Increase in the energy input would always be greater than the corresponding increase in losses in the compressor, and therefore, you continue to get a higher and higher efficiency.

At point B and beyond that, higher the input energy, the losses encountered by the compressor is higher than the input energy itself, which means that we are beginning to lose efficiency beyond this point B. So, beyond operating point of B, we kind of start losing efficiency, and beyond point C, the loss and efficiency becomes so high that the compressor operation itself is unstable because of the initiation of aerodynamic instabilities like stall or surge.

So, between these points or lines A and B where we could operate the compressor in a stable manner, but you would like to operate it as high an efficiency as possible, which is where A probably close to the point B where the rate of energy input continues to be much higher than the rate of losses or increase in losses. Beyond point B, the losses kind of start building and then energy input and the losses kind of huge mismatch between that, you begin to lose efficiency there. So, as we have seen, it is still possible to operate on the negative slope of the compressor map, but that is only an operational stability, from the operational stability point of view, but that is the region where the compressor operation is aerodynamically unstable and obviously you cannot operate in that region where compressor is aero dynamically unstable.

So, let us now start discussing about, see we have been talking about in stabilities in great detail, and what is meant by in stability like operational in stability and the aero dynamic in stability. Let us discuss about the aerodynamic in stability in little more detail. Now, I think I mentioned in the last class that, when we are talking about multistage compressor characteristics, that they are primarily two modes of instabilities that a compressor can encounter - one is to do with stall and the other is to do with surge. Now, we will first take up stall and understand stall in little more detail before we move on to surge. So, stall and surge are those two instability modes; a surge being the extreme instability and stall is probably a precursor to surge in some sense. So, let us take up stall first and what we mean by stall and what are the different types of stall that compressor can encounter.

So, stall basically can be attributed to, if you have undergone a basic aerodynamics course, if you have looked at flow passed and aerofoil, as we increase the angle of a diagonal of an aerofoil beyond a certain angle, you know that the aerofoil will stall. So, in come in, in, the compressor also we encounter phenomenon which is in some way similar to what you have learnt in the c l verses alpha curve. For example, that beyond a certain alpha or angle of attack, the, the, aerofoil stalls. So, if you look at it from a very simple perspective, compressor stall also in some sense originates or begins from kind of an aerofoil stall itself.

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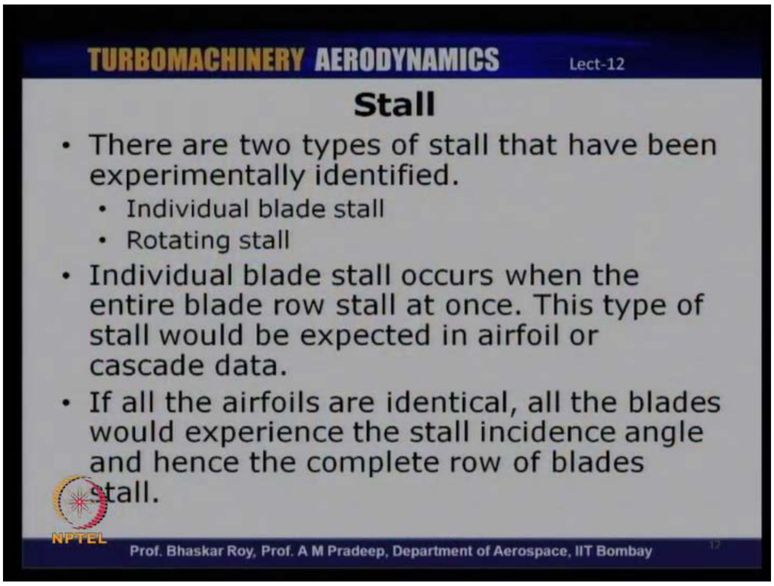

Now, there are two types of stall that we can associate with a compressor operation - one is to do with individual blade stall and the other is known as rotating stall. Now, individual blade stall occurs when the entire blade row would stall at ones and this is something that one would encounter or see. If you look at lets an aerofoil or (( )) like in cascade, we have already discussed about cascade, and one while carrying out lets a cascade experiment, since all the aerofoils are at the same stager and as you change the incidents, incidents of all the blades change simultaneously, and so, if there is stall encountered on one of the blades, it should be it should be the case that all the blades have stalled simultaneously because all of them have the same stagger and the incidents angles.

So, since all these aerofoils are identical like in a cascade, all of these blades are likely to stall and that is basically referring to an individual blade stall. Well, but in an actual compressor, we do not really have a scenario where all the blades are because it is in our cylindrical coordinates and is an unlike a cascade linear cascade where they are all arranged in a linear fashion. In a, in actual compressor, one is likely to encounter what is known as a rotating stall.

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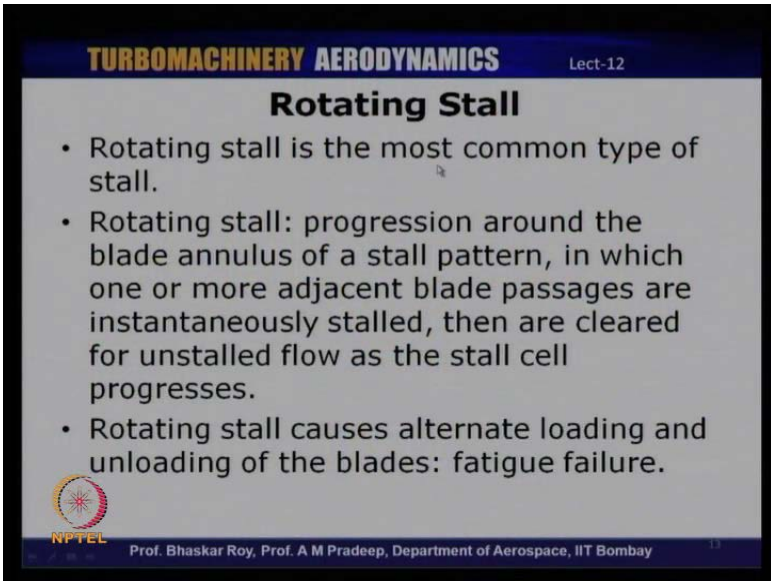

And we will discuss about rotating stall in some more detail and what is meant by rotating stall. So, rotating stall is the most common type of stall that one would encounter in an axial compressor. Rotating stall would basically involve progression around the blade analyze of a stall pattern in which, one or more adjacent blade passage is are instantaneously stalled, and then, cleared for unstall flow as stall cell progresses, that is, in rotating stall, one would have alternate stalling and unstalling of either one blade or a group of blades, that is, there would be a certain stall cell which would continuously move around the annulus. This is because the rotar it itself has a rotation, and therefore, the stall cell continuously moves, which is why it is known as rotating stall.

So, either 1 or is group of adjacent blades would be stalling and this stall cell progressively moves along the annulus of the compressor itself. Let us try to understand what is the mechanism of rotating stall and how it propagates. Now, let us consider as a tough blades of an a typical axial compressor that you see here.

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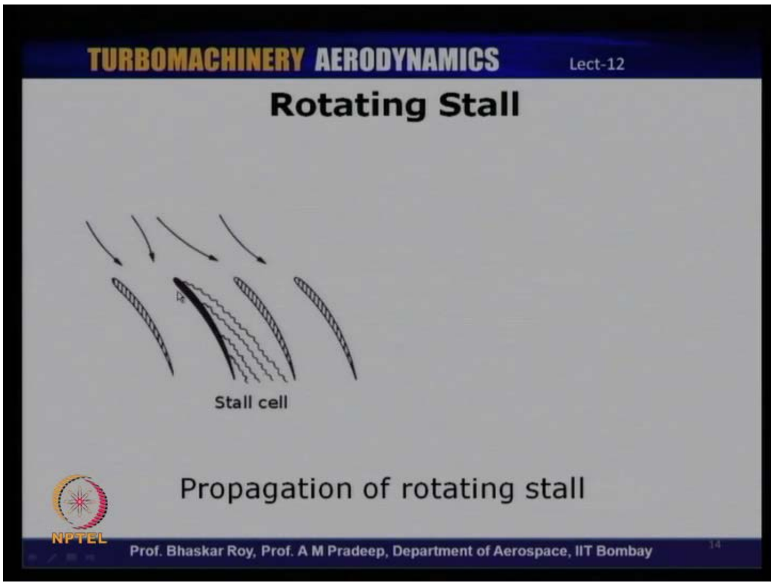

So, let us say, let us assume for the movement that due to some reason, it could be because of the incoming flow being non uniform or because of some local ratios with the stager of one of these blades are set of these blades that, the incidents angle to one of these blades exceeds the design value leading to stalling of this (( )). As you know that if this is you can kind of compare this with aerofoil characteristics c l alpha characteristics, as you keep increasing alpha. Beyond the certain angle, the flow stalls. So, something similar can be visualized here as well. That the incoming flow to, let us say other one blade or a set of blades has a higher incidence than what it should have mean leading to separation from one of the surfaces of the blade leading to stall.

So, what you see here is basically a stall cell. What we referred to as a stall cell? Now, this increased incidents and resulting in a stall of this blade basically causes the flow to enter the adjacent blade also with the higher incidents, but at the same time, it unloads the preceding blade, and since these blades are also moving, so the blades have a rotational direction in this direction. So, as these blades move and since the incidents continuously changes from one blade to another, what happens is the adjacent blade now sees a flow with a higher incidents than what it should have been, which means that this blade will now begin to stall.

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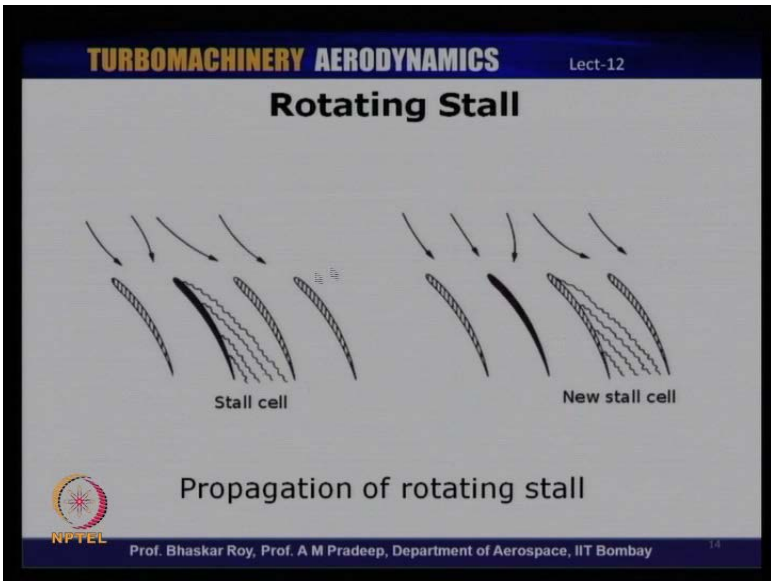

And as this blade adjacent blade stalls, what happens is that, now this blade has undergone stall and because of this stall which this blade has undergone. What basically happens is that this would unstall the previous blade which was earlier undergoing stall. This is moving to the fact that these blades are now are also rotating with the rotor speed. Now, so, as these blades rotate, the stall this blade which was earlier undergoing stall will now unstall and the stall now progresses to the next blade, and this continues, and therefore, what you see is the defectively one can see that the stall cell is now moving in a direction which is opposite to that of the rotor rotation itself. So, rotating stall usually has a direction of propagation in a direction opposite to that of the rotor.

So, here, we have visualized one blade which is undergoing stall. It is possible that there could be multiple blades which are undergoing stall and you may have multiple stall cells in fact propagating along the annulus of the compressor. We will also see some of these examples in some of latest lines. So, this is a typical mechanism by which rotating stall occurs, and in fact in the next lecture that, we will discuss basically will be attributing rotating stall to the effects to do with incoming flow itself, that is, the if the incoming flow is non uniform or what we refer to as a distorted inflow, that has an effect in initiating rotating stall in axial compressors.

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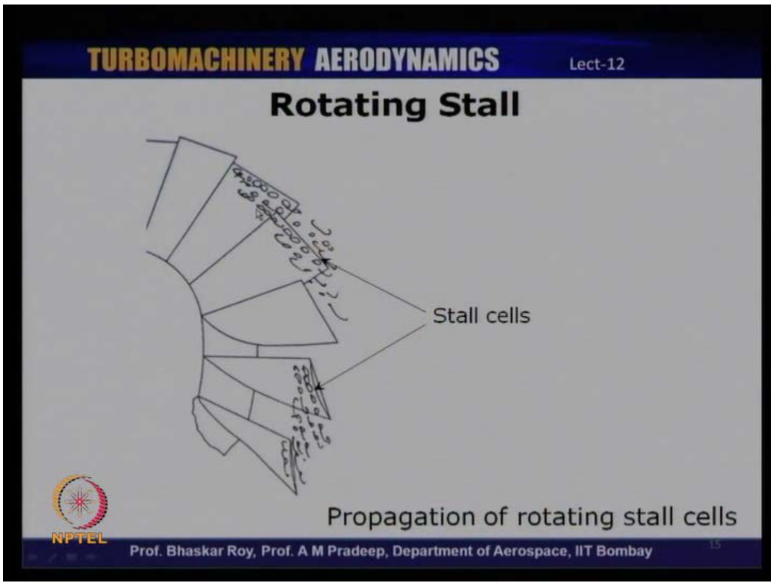

So, as I mention, you could also have more than one set of stalls, stall cells moving along the annulus like you see here, in this example, you have multiple stall cells which are propagating along the tip of the compressor blade. So, you could have multiple number of stall cells. You could have other one stalls cell or you could have number of stall cells, and in fact it has been observed that there are as high as nine stall cells which have been observed experimentally.

So, between one to nine or more, stall cells are possible, and so, what we were also see is that these number of stall cells also tell us something about the nature of stall themselves that is either one could have a mildly progressing stall or one could have what is known as an abrupt stall, and so, we will also see what are these two different types of rotating stall initiation mechanisms that are possible.

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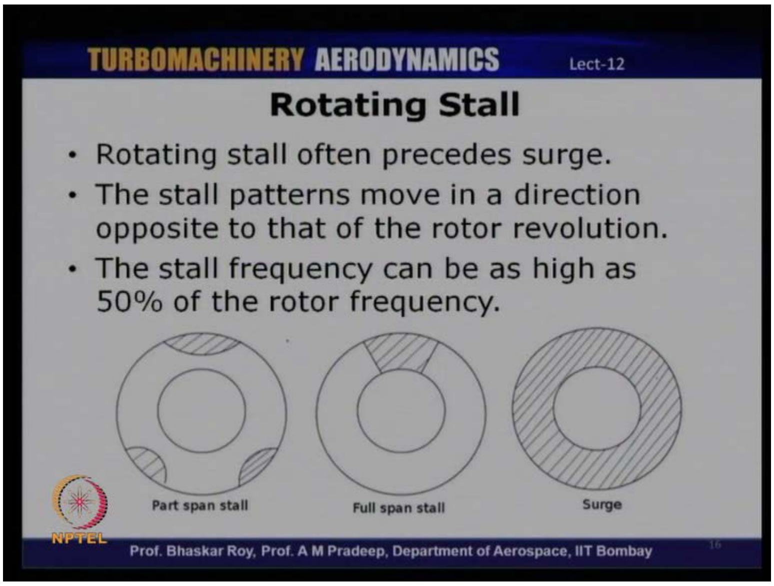

Now, it is also been absorbed that rotating stall it is also been observed that that rotating stall if allowed to progress and continue will lead to another instability or an extreme instability of operation of the compressor which is known as surge. We will discuss surge in little detail later on. The rotating stall often proceeds surge, and we have seen that the rotating stall propagates in a direction opposite to that of the rotor rotation and you could have rotating stall frequency as high as 50 percent of the rotor frequency itself.

You could also have stall in different types. You could have what is known as part span stall, that is, if this, if you consider this to be annulus of the compressor, this being the hub and this being the tip of the compressor. You could have stall which is extending only to a part of the span; it is not extending from the tip all the way to the hub, but there are multiple stall cells as you see here, or you could have full span stall as you can see here stall cell is extending all the way from the tip to the hub or you could have the entire annulus itself which has stalled, which is what would happen if we approach or enter into surge, which is why I mentioned that rotating stall often precedes surge.

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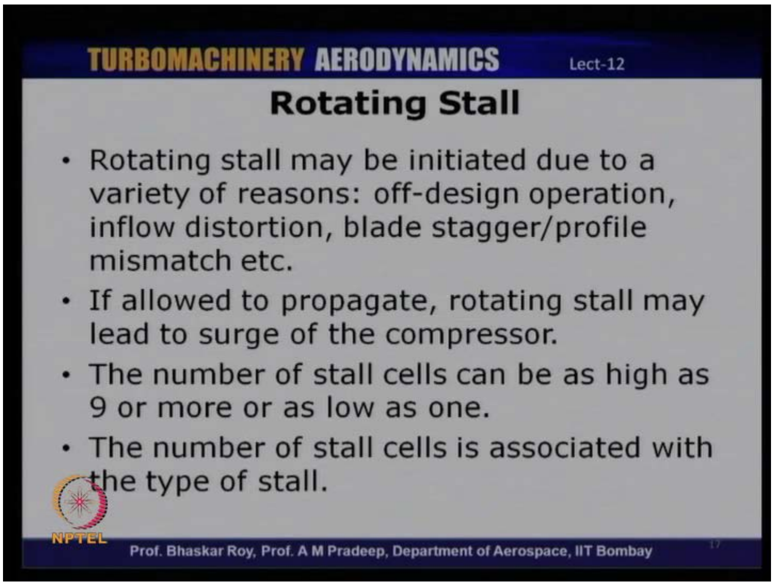

Now, rotating stall can as I mentioned be initiated by a variety of reasons. The most common being off design operation and the other common reason for initiation of rotating stall is inflow distortion, that is, if the incoming flow to the compressor itself is non uniform, that could be small pockets or regions where the local flow incidence approaching the compressor rotor would be much higher than the design incidence leading to initiation of stall in some of those blades, and once initiated, it will start begin to propagate, and if conditions are favorable, then the stall propagation is continues and it develops further, and in some cases, it can also bit dissipated if the conditions are not really favorable.

The other reason for rotating stall initiation could be slight mismatch in some of the blades having slightly higher stager or a slightly different profile due to certain manufacturing defect and so on, and so, once this kind of a compressor enters into slightly off design condition which possible that, these blades which have a slight mismatch in stager or profile will initiate rotating stall, and I have also mentioned that the number of stall cells can be as high as nine in some cases which I have been observed or as low as one, and number of these stall cells is also associated with the type of stall.

So, there are two types of stall which I have been observed experimentally - one is to what is around known as progressive stall and the other is known as abrupt stall, and some of the latest literature refer to these modes of stall as the model inception of stall are spike initiated stall, that is, if in some cases stall is initiated in a progressive manner in a mild manner which basically also referred to as model inspectional stall or you could have an abrupt or sudden initiation of stall is also are referred to us spike initiated stall. Now, in progressive stall, we have a gradual reduction in total pressure ratio after initiation of stall, whereas in abrupt stall there is a descried jump or decrease in the pressure ration as stall is initiated.

Now progressive stall is usually associated with multiple stall cells. You could have more number of stall cells which is why one would have progressively decreasing pressure ratio, and in an abrupt stall, it has been absorbed that it is initiated with one stall cell, but that is a largest stall cell extending all the way from the hub to take.

So, progressive stall are model stall inception usually is associated with multiple stall cells which are propagating abrupt stall or spike initiate stall is usually referred, associated with a single, a single stall cell which initiates this kind of a stall. So, if you look at characteristics, compressor characteristics where we can try to understand these two modes of stall.

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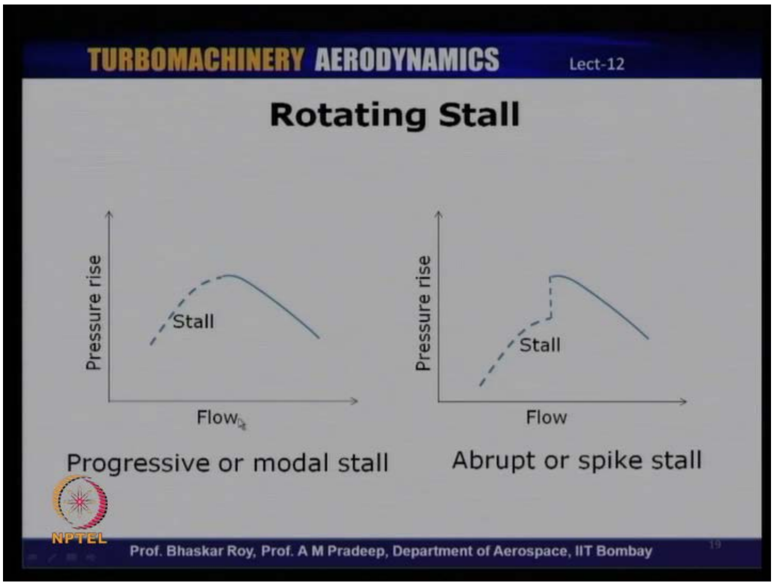

On the graph that you see here on the left hand side, we have pressure rise versus flow. The compressor characteristic operating all the way from choke with decrease in mass flow or as with throttle the compressor leading to higher and higher pressure ratio peak pressure ratio and then the pressure ration begins to drop.

So, this is a typical progressive or model stall inception, whereas on the right hand side, what you see here is that the compressor characteristic continues to increase up to the peak pressure, and then, there is a discreet jump or drop in pressure ratio and the compressor enters into stall. So, this is typical spike initiated stall or abrupt stall which has been in encountered by this kind of a compressor. So, these are two different modes of compressor stall which have been observed by different researches and they are tribute the, the, of course, there are lot of mechanisms and theories which are have been kind of proposed on why this kind of stall mechanism is initiated and so on, which I guess will not go into details of that. So, in let us say for example, we consider just the progressive stall. Let us try to look at what really happens when progressive stall is initiated.

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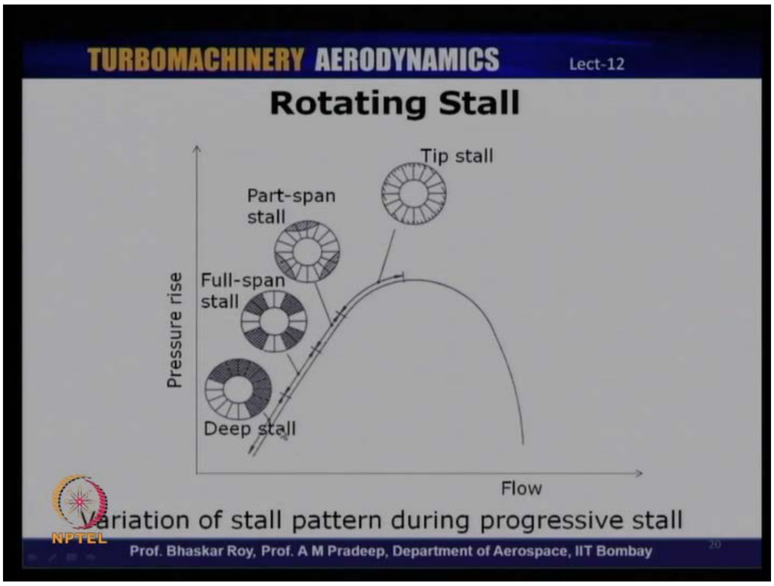

So, this chart here basically shows us variation of stall pattern in a typical progressive stall will not necessarily true for all the cases, but this, in this particular case, what has been observed is how progressive stall kind of can be explained in by using these characteristics. So, let us say stall has been initiated as you increase the or as you throttle the mass flow, we have an increase in pressure ratio; we reach the peak pressure point, and since this is the progressive stall, we have a gradual decrease in the pressure rise characteristics.

So, what really happens in this scenario that, in just to mention here, in most of the compressors that we encounter stall is initiated from the tip of the blades. So, which is basically referred to as a tip critical rotor or stall is initiated from the tip of the rotor which is true for most of the compressors of course, there are exceptions also where stall could also be initiated from the hub, but the, those are relatively rare.

So, as you enter into the negative slope of the compressor characteristic, we have stall being initiated form the tip, and as we progress further down, we have part span stall; we have multiple stall cells. Then this extends to full span stall, and then, of course, we are going to deep stall where the whole large fraction of the annulus has stall flow. So, this is typically how a progressive stall would evolve and develop. So, having understood about rotating stall, let us now quickly look at the other mode of instability which is probably a more serious mode of instability that is surge.

Now, I mentioned of course that it is possible that, when stall in the, enter into deep stall, full annuluses under stall. You could also lead this; obviously, could also lead to surge. Now, what happens in surge is a complete breakdown of stable operation of the compressor flow and there is a violent oscillation of mass flow back and forth along the length of the compressor.

So, this is typical of a multistage axial compressor. What basically happens is that, as you are operating left hand side of the compressor characteristic, any decrease in mass flow rate will be accompanied by a corresponding or greater decrease in the pressure ratio, and therefore, there is a drop in pressure ratio which may not be matching with the pressure ratio downstream, and so, that leads to a back flow from the downstream all the way to the upstream of the compressor, and though this kind of mass flow, fluctuates back and forth in the compressor, and as you can visualize, this is a complete breakdown of the mass flow and leads to failure of the compressor operation itself which eventually; obviously, also leads to failure of the engine could lead to engine shutdown and so on.

So, that this is a very extreme case of instability of the compressor which obviously something that all designers would want to prevent, and which is why I will be mentioning about surge margin which is provided in all axial compressor operation. This is a band in which the compressor is stable and one should not exceed the surge margin because the compressor is likely to encounter surge.

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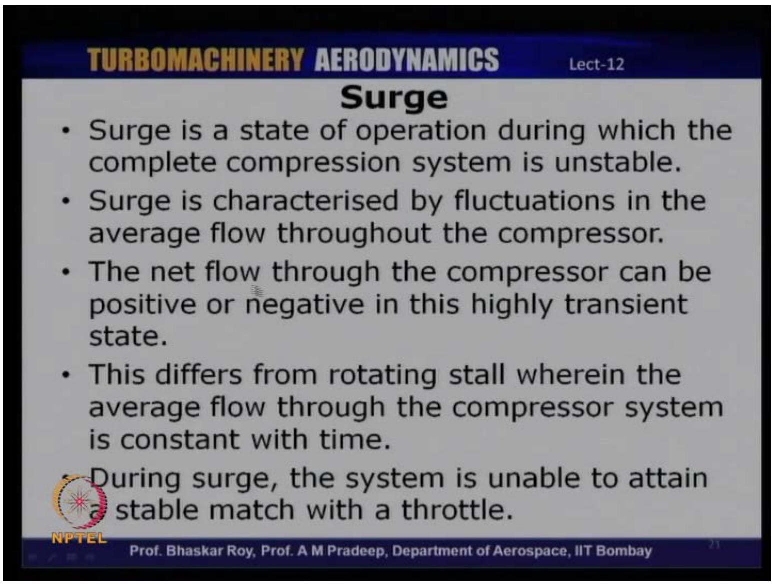

Now, surge is basically characterized by fluctuations in the average flow throughout the compressor, and in this case, the net flow through the compressor can either be positive or negative when its highly transient phenomenon, and this is different from rotating stall where in there is still an average flow which is passing through the compressor and is constant with time, but during surge, this system obviously is unable to attain a stable match with a throttle which is downstream.

Now, in the compressor operating line, we have seen the surge line which basically denotes the locus of unstable operation of the compressor and surge obviously may lead to flame blow out in the combustion chamber and can obviously lead to substantial damage of the compressor itself. So, during a design of a compressor, there is a certain margin which has been provided by the designer, where in one is recommended to operate the compressor which is known as operating line and there is a difference between the operating line to the surge lines.

So, that is basically the surge margin. That is the margin which has been provided for operating this compressor, that is, even under off design conditions, one should ensure that the off design operating point is still away from the surge line. It is not very close to the surge line, because if it is too close the surge line, there is always a risk that the compressor might get pushed into surge which is obviously detrimental as we have seen.

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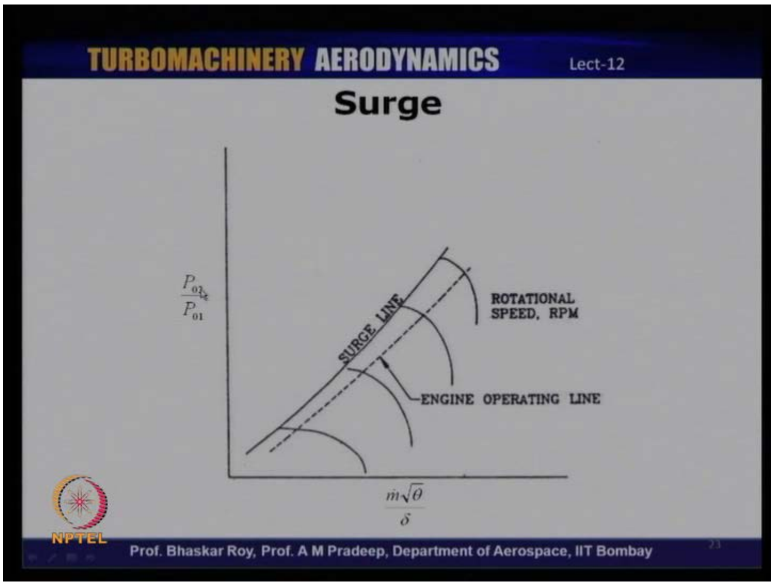

So, if you look at this a compressor map which I had shown earlier as well, this is the surge line its locus of all the surge points. If you join the surge point at different operating speeds, then we get what is known as the surge line, and this dotted line is a engine operating line, and so, this difference is basically referred to at the surge margin.

And modern day compressors are designed to operate with a very small or narrow surge margin and that is basically to ensure that the compressor is operating with a fairly high efficiency delivering a high level of pressure ratio. At the same time, we would also want to ensure that the compressor does not move very close to the surge line because obviously that is quite risky.

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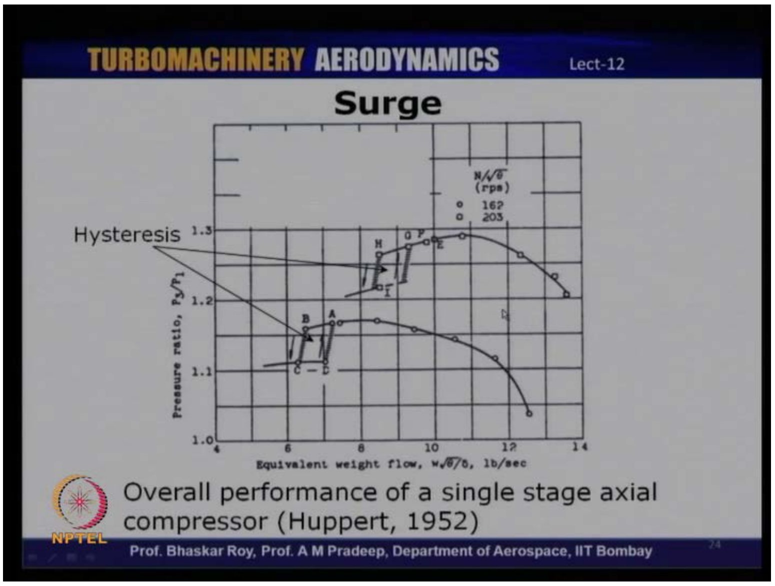

So, let us now look at some of this example, some examples of actual experiments which have been carried out several years ago. This is one classical example of characteristic a single stage characteristic as its shown here from a old paper by huppert in 1952. As you can see, it is more than 50 years old, but this is still considered by this is still considered to a classical paper because it explains lot of the issues related to surge. So, here, you can see its compressor operation at two different speeds, and what you can see is also what I have referred to as hysteresis.

I will probably explain this in little more detail in the next class, but what you see here is a as the compressor enters into surge between points a to b, this as you can see there is a sudden drop in the performance characteristic, and as you try to recover the compressor operation from its surge line or surge point back to stable operating range, it does not trace the same path and this loop as you see here is basically referred to as hysteresis.

You might be familiar with hysteresis of magnetic materials, paramagnetic materials. So, this is a similar aspect which is observed in compressors as well as the compressor enters into surge or deep stall, and if you recover from the surge or deep stall operation, the operating points are slightly different and that is attributed to hysteresis. I will explain that in more detail in the next class.

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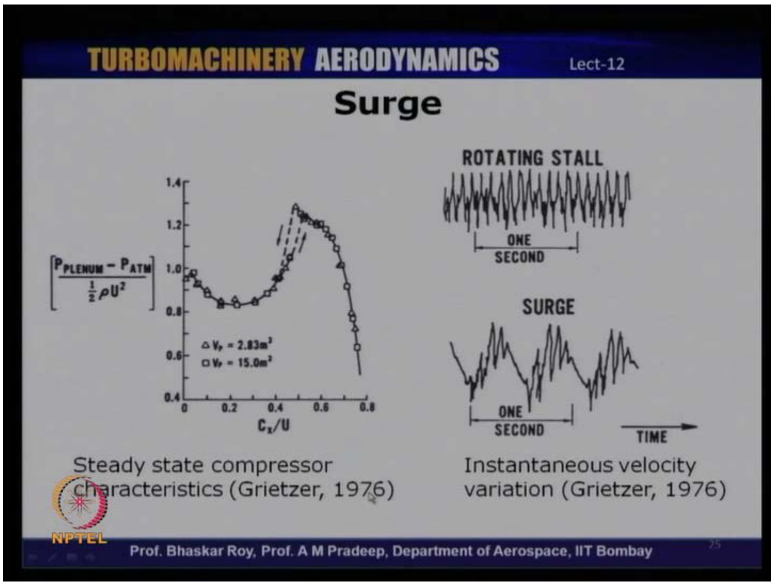

Now, there is one more example that I would like to show here. This is from again an old paper by grietzer and his group at m i t, and so, this is also explaining the hysteresis and associated with surge and its initiation. So, as the compressor operation is taken from its choke point all the way to peak pressure and you can see there is an abrupt stall and surge operating or the compressor basically enters into a surge mode of operation, and once it is taken out of that mode of operation, it takes a different path and that is basically a attributed as I mentioned to hysteresis.

So, that is also seen in this particular characteristic as you can see. Now, what grietzer also observed in his experiments was the effect of rotating stall and surge and we can see how these instabilities were actually measured in terms of velocity variation. So, if you were to measure variation of velocity in a compressor which is let us say undergoing rotating stall, one would see fluctuations as we can see several fluctuations within a second, which means that the frequency of rotating stall is several magnitudes higher than that of surge.

You can see this in surge, one second has probably just one or few fluctuations, whereas in rotating stall, you have several fluctuations taking place in, in, an a second. So, the frequency of rotating stall is usually at least one order magnitude higher than that of surge, and in surge, you can the fluctuations which are basically axis-symmetry and the flow basically moves back and forth with a frequency which is much less than that of rotating stall.

As I mention, rotating stall can have frequencies as high as 50 percent of the rotor frequency itself, and which means that rotating stall can indicate have very high frequency. Surge on the other hand is not related to really related to the rotor frequency; it is just axis-symmetric motion, motion, of flow back and forth in the compressor which could have very low frequencies usually one order less than what is encountered in rotating stall. So, this is just to summarize the different modes of instabilities what we have discussed in today’s lecture of course, there are few more aspects that need to be discussed and I guess I will take that up in the next class where ill also talk about what I mentioned in the last slide about hysteresis and so on, and we will obviously discuss lot more details of instabilities and inflow conditions on instabilities later.

So, in today’s lecture, basically we discussed about instability in general and instability as applied to compressors and what we mean by instability of axial compressors. We have seen there are two modes of instabilities in general - the operational instability and the aerodynamic instability, and in, we have also seen that even though it is theoretically possible to operate on the positive slope of an axial compressor map where operational stability can be maintained; it is aerodynamically not unstable, and there are different modes of aerodynamic instability. We have seen rotating stall and surge being the major modes of instability.

Rotating stall obviously involves a set of stall either one or more stall cells moving along the annulus of the compressor in the direction that is opposite to that of the rotor rotation, and rotating stall could be other part span or full span or deep stall. So, you could have either of these modes in rotating stall. Surge is an extreme instability which is encountered in an axial compressor, where in the compressor operation, there is a complete breakdown or stable operation of the compressor and it is a highly transient phenomenon where there is movement of mass flow along the length of the compressor back and forth and it is axis-symmetry rotation.

Rotating stall is not axis-symmetry, whereas surge is axis-symmetry; that means, the entire annulus will be undergoing this instability, whereas in rotating stall, we have seen that it does not the entire annulus. It affects only the part of the annulus which is why rotating stall is not axis-symmetry; surge is an indeed axis-symmetry.

You have also seen that rotating stall can have a very high frequency of a, of as high as 50 percent of the rotor frequency itself. Surge on the other hand is characterized by very low frequencies, usually one order of magnitude less than that of rotating stall. So, these are the different instability modes that kind of effect the performance of the compressor and it is important for us to understand this, because this limit of operation of the compressor puts a limit on the operation on the whole engine itself and engine operation obviously cannot take place at points which are beyond the stable operating limits of the compressor, and that is why we had I was emphasizing the importance of understanding these instability and stable operating modes of the compressor.

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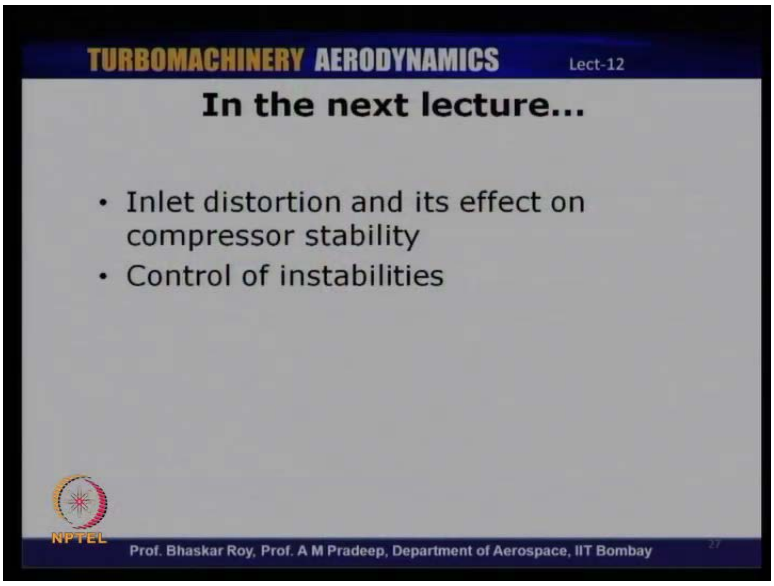

So, in the next class as I mentioned, we will take up instabilities little more discussion on instabilities. We will talk about the effect of distortion on the performance or stability of the compressor. We will also spend some time on discussion on methods of controlling these instabilities, because obviously we would like to control instabilities. At the same time, we would also like to operate the compressor as close as possible to the highest efficiency point which incidentally might lie very close to the surge line, and so, we would also like to explore mechanisms of methods by which these instabilities if initiated can be controlled so that the range of operation of the compressor can be extended. So, we will take up some of these topics for discussion in the next lecture.