Turbomachinery Aerodyanmics

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Lecture No. # 04

2-D Losses in axial flow compressor

Stage: Primary losses

Hello and welcome to lecture number 4 of this lecture series on turbo machinery aerodynamics. We have been talking about the fundamentals of axial flow compressors and in the last couple of lectures, we have had some discussion on the various aspects of the fundamental aerodynamics involving axial flow compressors.

We also had lot of discussion on the various nomenclature, and terminologies that are used in axial flow compressor analysis, and subsequently design of axial flow compressors. So, we have been discussing about the various aspects that are involved in design, as well as the nomenclature associated with the fundamental axial flow compressors.

In the last lecture, for example, we were talking about what are known as cascades? And the aerodynamics is associated with cascades - cascades if you recall are vey simplified versions of axial flow compressor geometries where in one can get very lot more details, in terms of the measurements that can be carried out on an axial flow compressor blade and it also gives us the fundamentals of understanding of the aerodynamics of flow in axial flow compressors.

So, cascade analysis plays a very significant role in terms of the understanding of the two-dimensional geometry of of an axial flow compressor blade. So, before one undertakes a very detailed design and development of the complex 3-D geometries, which are involved in a modern day axial compressors, a cascade analysis and cascade experiments, would give us a great insight into the performance, as well as the various characteristics associated on the flow physics associated with the flow in an axial flow compressor. Although, in a very simplified format, because the actual flow in an axial flow compressor is highly three-dimensional which is something - which is not captured in a cascade analysis.

Nevertheless cascade analysis does give us a lot of insight into what is going to happen in a design of a particular geometry of an axial compressor blade? So, what we going to do today is to continue discussion on cascades for some time, and subsequently discuss about losses which are involved on a two-dimensional scale. So, the 2-D losses associated with the compressor is what we will discuss in lot detail in today's lecture? So, today is lecture is going to be about following topics.

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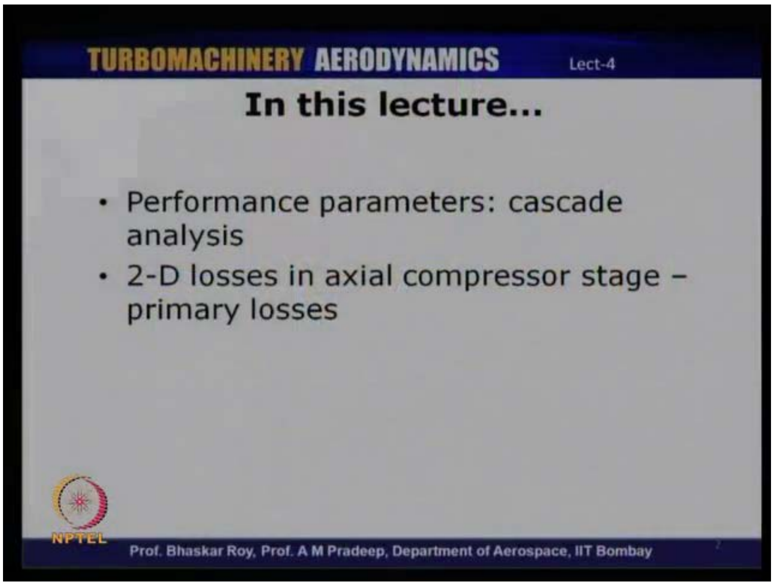

We will start with performance parameters which are associated with cascades and subsequently, we will spend lot of time discussing about the two-dimensional losses associated with an axial compressor stage. So, before we take our discussion to the loss different loss parameters involved, let us discuss about the performance parameters, which one can expect from a cascade analysis.

So, basically there are 2 distinct performance parameters that one can derive from a cascade analysis. Although, one may take a variety of measurements in a cascade; there are basically 2 parameters that one would be interested in that is something that the designer would be very much interested in knowing, as to what these two parameters are?

And these parameters are, one is the total pressure loss that is involved in a particular cascade geometry, and the second is the static pressure coefficient that is the pressure rise on the blade surface. So, loss the first parameter being the loss, it gives us an indication of what are the kind of losses that one can expect from a particular cascade geometry? And which obviously also will give us some hint towards, what the efficiency of such a compressor would is likely to be.

The second parameter being static pressure coefficient. Static pressure coefficient is measured on the blade surface and this therefore, is an indication of the blade loading. So, the amount of load that the blade is designed to be is something that can be derived from the static pressure coefficient, which basically involves measurement of static pressure on the blade surface.

And so, these are the 2 parameters that we are going to discuss in detail for a sometime today, subsequently we will of course, we be discussing about the various losses involved. So, let us first talk about the total pressure loss coefficient.

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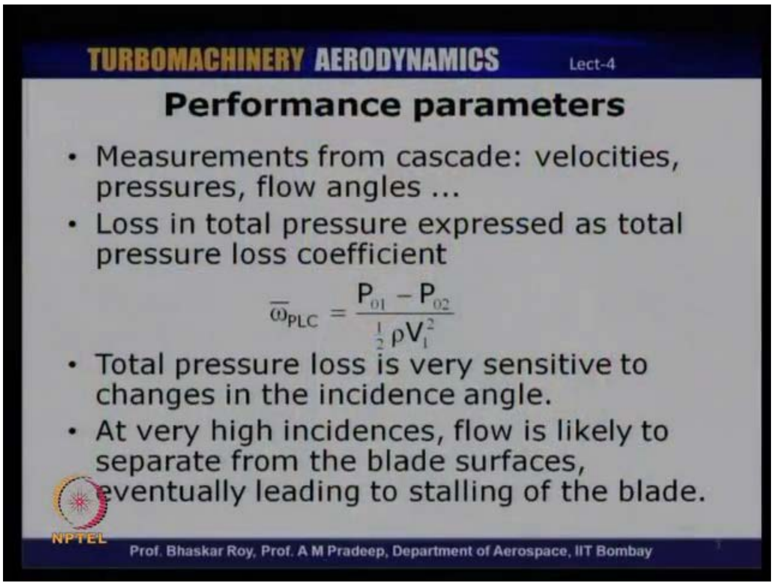

Now, in a cascade of course, various measurements that one can carry out in a cascade can vary from velocities, the different components of velocities, then the total pressures, the static pressures, as well as the flow angles. So, from these measurements that one carries out in a cascade. One of the parameters that we can derive is the total pressure loss coefficient.

This basically is an indication of the loss in total pressure that one is likely to encounter, in a particular cascade and so, total pressure loss coefficient is design defined as P 0 1 minus P 0 2 divided by half rho V 1 square; so, here P 0 1 refers to the total pressure at the inlet of the cascade, P 0 2 is the total pressure loss at the exit or at the trailing edge and the denominator refers to the dynamic pressure at the inlet; where rho is the density and V 1 refers to the velocity at the inlet of the cascade.

And total pressure loss is or in fact in general losses are usually expressed, and in expressed in the form of the symbol that is omega - omega with a bar at the top means, an average total pressure loss. So, omega bar refers to the average total pressure loss at the trailing edge of a particular cascade, and PLC the subscribe refers to pressure loss coefficient.

Now, as you can see here, pressure loss basically depends upon of course, the difference in total pressure between the inlet of the cascade and the exit of the cascade, and with reference to the dynamic pressure that is available for the cascade. Now, in an axial compressor rotor for example, you would not encounter a total pressure loss in the absolute frame of reference, because there is energy added in the compressor and therefore, that manifest itself in the form of a rise in total pressure. But, there is a loss in total pressure in the relative frame of reference which of course, we will discuss in lot more detail in later lectures.

So, the total pressure loss coefficient that you have just seen here is difference in the total pressure loss between the inlet and the exit of the cascade, with reference to the dynamic pressure. Now, this total pressure loss is very sensitive to the angle, at which the flow enters the cascade. The or… The incidence angle as we have discussed in the last class. So, this total pressure loss is highly sensitive to the incidence angle and we will see, how it varies as the incidence angle changes.

So, that something we will discuss in little more detail later. That, as the incidence angle increases, there is also a tremendous increase in the total pressure loss and beyond a certain point, the total pressure loss increases substantially to such an extent that one can qualify the cascade to have stalled.

So, at very high angles of incidence; for example, if I am assuming that you have seen CL verses alpha curve for an airfoil that is as to keep increasing the angle of an attack of an airfoil. The lift coefficient increases, but that increases only up to a certain point, after which the lift coefficient drops drastically and this is the point, which refer to as stall for an airfoil.

So, very similar thing happens in the case of a cascade also, because the compressor blades are basically aerodynamic bodies and are airfoil shapes. Which means in a two-dimensional sense, they behave like an airfoil. So, there is a certain stalling angle which in this case the angle of attack refers to the incidence angle. So, at a certain angle of incidence, the blade can stalled, leading to substantial increase in total pressure.

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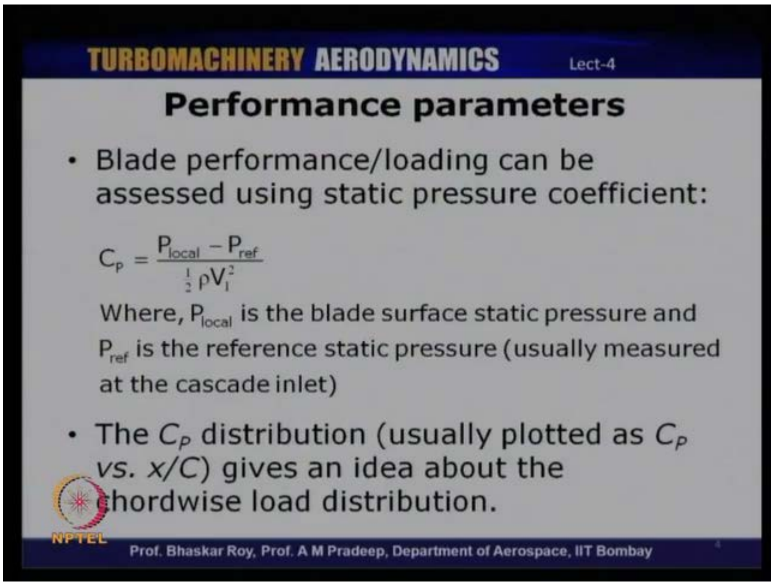

So, total pressure loss is one of the parameters that one would be interested and what is the other parameter? The other parameter that we can infer from the cascade study is the static pressure coefficient, which is denoted by C P; C subscript P, and C P refers to static pressure coefficient of a cascade, and C P is measured or calculated as P local minus P ref divided by half rho V 1 square; where, P local is the blade surfaces static pressure that is at each individual point on the blade surface, We take a static pressure where that refers to that is basically the local static pressure, and P ref is the reference static pressure usually, this is measured at the cascade inlet.

And from a cascade study, one would normally express this C P distribution in the form of C P verses non-dimensional axial length, which is x by C that is where C is the code. So, C P verses x by C is the C P distribution, and C P distribution in some sense integration of this C P distribution is basically the loading of the blade. So, C P distribution can give us an indication of the loading of a compressor blade; which is while C P also plays a very significant role for a designer, because C P is indicating the load that is the loading associated with compressor blade and therefore, a designer has a lot to learn from the C P distribution that is obtained from cascade studies.

So, from a typical cascade analysis, these are the 2 fundamental parameters; that one can expect, one is the total pressure loss coefficient, and the other is the static pressure on the blade surface or the C P distribution. And so, how is it that one can express, these performance parameter; and what is it that one can gain from looking at the magnitude of these parameters?

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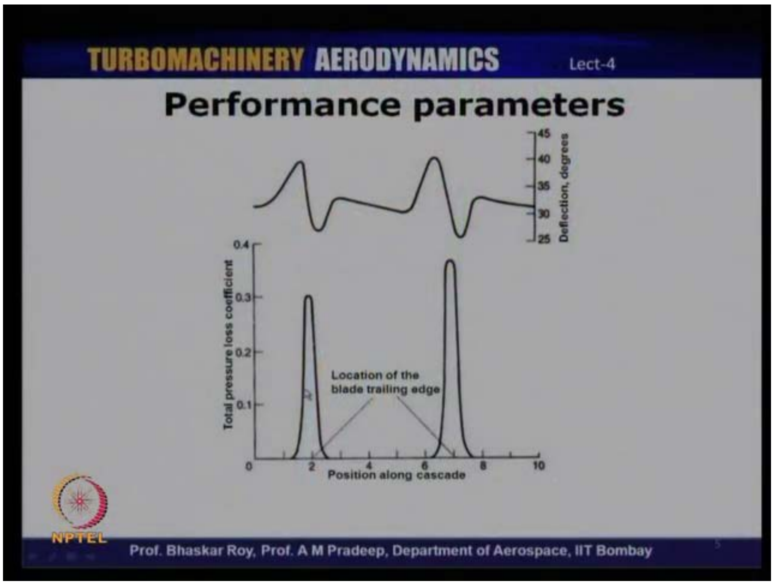

Let us take a look at the total pressure distribution on a cascade. So, if you look at the total pressure distribution; so, I have what I have plotted here are of two different graph. One is the total pressure loss coefficient or omega, and the second is the deflection angle that is at the trailing edge and so, these are the 2 different parameters that we are looking at.

And on the x axis, we have position along the cascade that is along the cascade axis and the 2 distinct positions which have been marked here, one both of these correspond to location of the blade trailing edge. So, as you traverse or move a probe from one end of a cascade to the other end, the probe would basically see different trailing edges of different blades.

If you are measuring total pressure from the total pressure probe, there are certain points where, there is a very drastic rise in the total pressure rise. Total pressure loss coefficient you can see here, that there are two distinct peeks which you can see which correspond to very substantial increase in total pressure loss, else were the losses are close to 0.

So, these 2 points correspond to the trailing edge of 2 different blades. So, there are 2 blades here, trailing edge of these blades have those regions where, there is a substantial amount of viscous dissipation and losses and therefore, there is a total pressure loss occurring in occurring at these locations and the total pressure loss peek at these locations. In this what is indicated here, in terms of increased total pressure loss at two distinct trailing edge locations.

Now, the other parameter that I have plotted here is the deflection angle. Deflection angle is basically the angle, at the trailing edge as you measure at the trailing edge, very similar to the incidence angle which is measure at the leading edge, we also have a deflection angle which is measured at the trailing edge. So, as you approach the trailing edge, one can obviously see a substantial increase in the deflection.

So, what you see here is that other than the trailing edge of the blades, at mid span locations or mid passage locations, the losses are very low. There is again any total pressure loss at those locations which is expected, because in the mid span mid passage location, the flow is close to potential flow, there is there no viscous losses taking place their and there no reason for any total pressure loss occurring in in these regions.

Whereas, close to the trailing edge is where the viscous effects nominate and one would see certain amount of total pressure loss in the trailing edge regions of different blades, and which is what is indicated by this increased total pressure loss, just around the trailing edge of these blades.

Now, I mentioned, if you recover a few minutes ago that as you increase the incidence angle beyond the certain incidence the blades tense to stall, and what is meant by stalling is? I assume that you have already seen airfoil stall that is at certain angle of tags airfoil, the flow separation begins at the on the suction surface of an airfoil for positive incidences and as you keep increasing, the incidence angle, the flow region or the extent of flow separation increases, to such a region point that beyond a certain point, the flow separation engulfs the entire suction surface leading to what is known as stalling of the blade?

We are likely to see a very similar thing happening even in a cascade, as you change the incidence angle. As the incidence angle increases beyond certain level, the cascade also experiences, what are what is known as blades stall?

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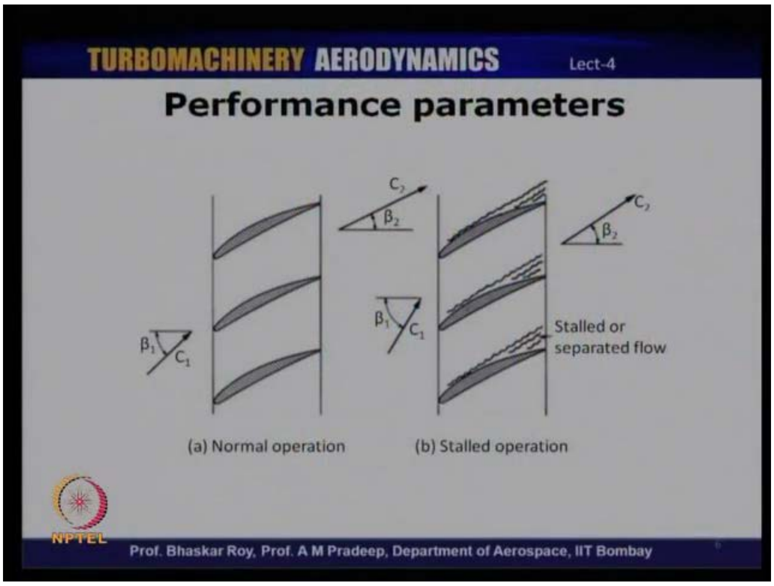

Let us take a look at one example of a cascade, which is operating under 2 different modes or conditions. The first one is the normal mode of operation where there is hardly any total pressure loss taking place, and the flow is very much aligned to the the blade surface, as you can see here. The the velocity vector is in the direction of the blade, angle at the leading edge and therefore, the flow is well behaved.

There is no flow separation taking place, but as you increase the angle of a tag or the incidence angle from the suction surface incidence the positive incidence that is taking place here. There is flow separation taking place from the suction surface of the airfoil, and this is what is refer to as a stalled or separated operation of the compressor of the cascade? So, for as you keep increasing the angle of incidence; one is likely, to encounter separated flow from the suction surface for positive incidence, and for negative incidence one might see separation from the pressure surface of the cascade.

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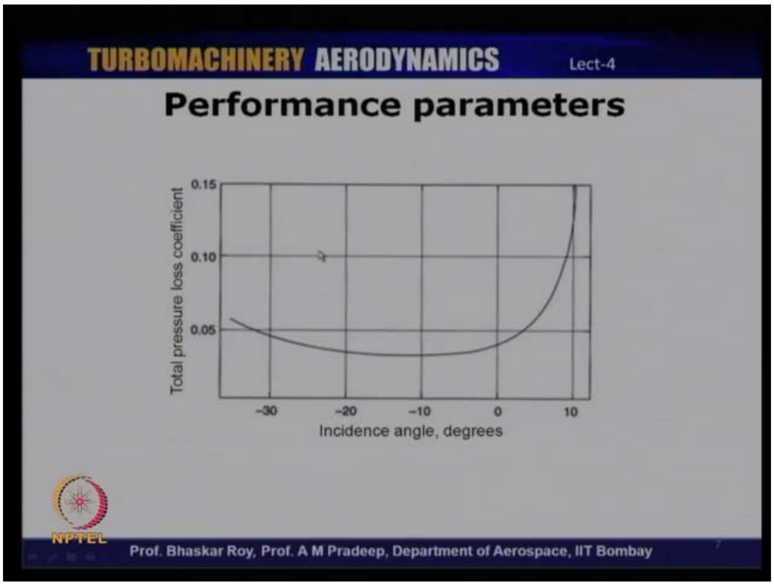

Now, I also mentioned, that total pressure loss is extremely sensitive to the incidence angle. So, I have now, plotted total pressure loss verses incidence angle. That is how total pressure loss is function or how does it depend upon the incidence angle. So, as you change incidence angle one can see that total pressure loss changes drastically, and that is more true for negative, for positive incidence angle that is total pressure loss increases drastically; for increased positive incidence angle. Around 0 degrees and few negative incidence angles, total pressure loss is more or less constant beyond, which again total pressure loss increases.

Now, as a thumb rule, what people have kind of observed is that as you keep increasing the incidence angle, and if we notice that the total pressure loss has doubled than the angle at which the total pressure loss has doubled is kind of taken as the point at which the cascade has stalled. So, doubled the total pressure loss as compare to the lowest total pressure loss, indicates the angle of incidence for which the blade has stalled.

Because this is empirical kind of a thumb rule which people have observed by carrying out experiments over several cascade blades that, this kind of a thumb rule has been arrived at. So, let me quickly recap, what I have been talking about in the last few minutes. We were discussing about the performance parameters associated with cascades and how is it that we can use cascade data, in terms of the data that is achieved obtained from a cascade, how is it that that we can make use of the cascade data.

Now, in the next part of this lecture, that I am that we shall be discussing, we will be talking about losses in a compressor blade. We will be focusing our discussion on the 2-D losses associated with compressor blade, and we will of course be discussing more details about the 3-D losses in separate lecture. In today's lecture, we will basically be talking about the 2-dimensional losses in a compressor.

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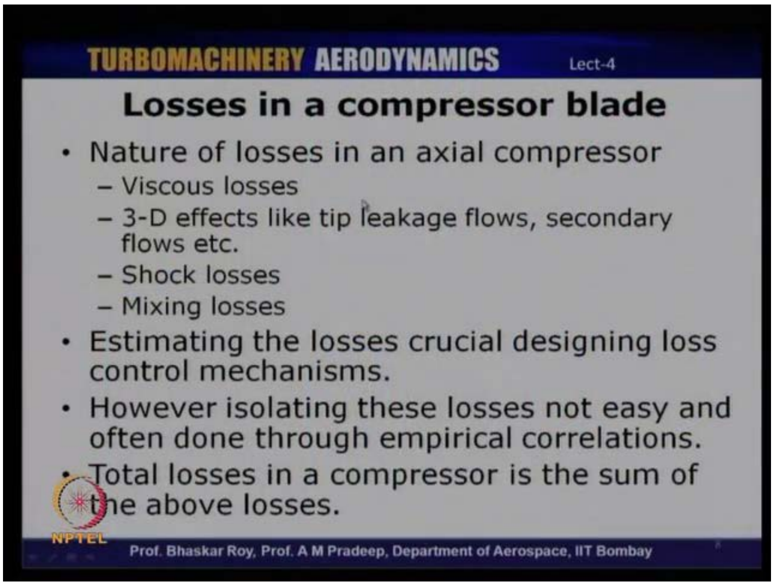

So, before I discuss about the 2-D losses, let me also discuss about losses in general, in a compressor blade. Now, there are different ways of classifying losses in compressor in a axial compressor. One set of losses is refer to as viscous losses like for example, the total pressure loss which I discussed, with reference to a cascade is a kind of a viscous loss.

There are whole lot of losses associated with the three-dimensional flow. These are known as 3-D losses or 3-D effects losses like tip leakage flows and secondary flows etcetera. In a transonic compressor, one may also encounter shock losses and there are also losses associated with mixing, taking place of the mixing of the shear layer, taking place of the trailing edge of the blade and refer to as the mixing losses.

So, it is very important for a designer to understand the various types of losses and the origin of these losses. Because it is basically, an indication of the performance of the blade itself and estimating the amount of looses that particular blade is likely to encore is very important aspect of the hole design process itself.

So, we will, today we discussing about the losses which are associated with two-dimensional flow in a 2-D sense basically that we can classify losses, also in terms of 2-D losses, as well as 3-D losses like what we have discussed know and we will see that there are certain types of losses, which we can es[timate]…Which we can empirically calculate by assuming certain simplifications on the geometry as well as the flow, and arrived at certain empirical correlations for estimating these losses.

So, we will be discussing about some of these losses in today's lecture, and we will also discuss detailed loss estimation associated with the three-dimensional flows like the tip leakage flows, and secondary flows in a separate lecture. So, estimating these losses as I mentioned is very crucial, it is primarily in the sense that if we have to design a blade which has lower losses or design loss control mechanism. Estimation of these losses is is very crucial, and the main difficulty associated with estimation of these losses, is the fact that from the measurements that one carries out in in experiments or even in in computations, isolating these losses into different components. It is it is often a very difficult task, as to how we can distinguish between these different losses and the many many a times when we take measurements or even from computational data, what we get is an estimate of combination of different losses, not individual losses itself.

So, for a compressor, if you were to talk about the total losses talking place across a compressor blade, then it is a sum total of all these different forms of losses like this viscous loss or 3-D losses or shock losses or the mixing losses. Some total of all this losses put together, gives us an indication of the total losses taking place in a compressor.

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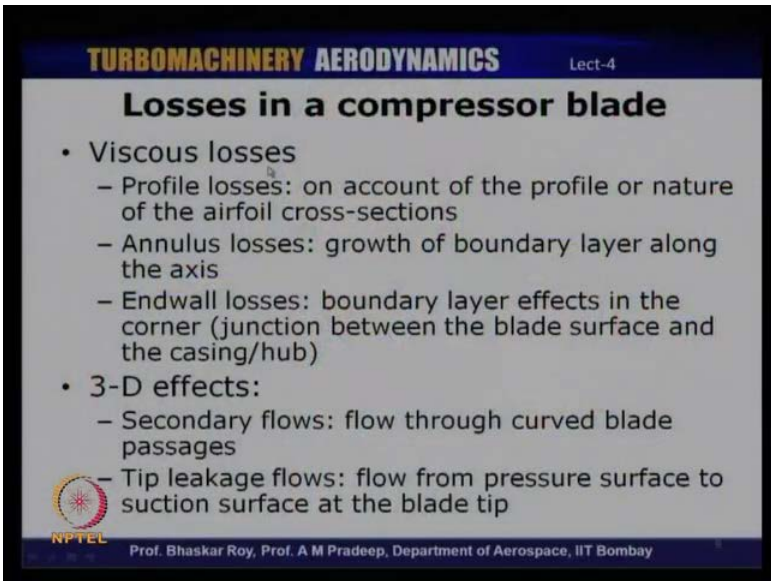

So, let us talk about these losses in little more detail. We first talk about viscous losses. Now, viscous losses can be attributed to at least 3 different sources. One is the profile loss, which is on account of the profile or nature of the airfoil itself that is basically the viscous effect on the blade surface. Annulus loss is, basically attributed to the growth of boundary layer along the axis of the compressor, especially for a multi stage axial compressor, it can be quite significant.

Endwall losses, basically refer to the boundary layer effects in the corner or the junction between the blade surface and the casing or hub. The other set of losses, the 3-D effects as I mentioned, one could have secondary flows, which we will discuss in detail later on flow through. Secondary flow basically occur as flow passes, through a curved blade passage.

Tip leakage flow is basically referring to the flow from the pressure surface to the suction surface at the blade tip. Basically true for rotors or stators which are hung from the casing. So, these are two distinct forms of losses besides of course, there are shock losses and mach and the mixing losses which we will discussion towards the end of this lecture. And viscous loss is what we will be discussing in terms of the 2-D losses that associated that are associated with compressor blade, 3-D losses will be discussed in detail in a separate lecture.

So, before I discuss about 2-D losses in general. What we will do now, is to relate the losses, in a thermodynamics sense to the entropy rise across a rotor. Because, if you recall from fundamental thermodynamics, any loss generating mechanism would obviously lead to an increase in entropy.

So, we can in principle relate entropy rise across a compressor to the losses that are taking place across the compressor itself. So, that is what we are going to do? And try and relate the entropy to the losses across a compressor.

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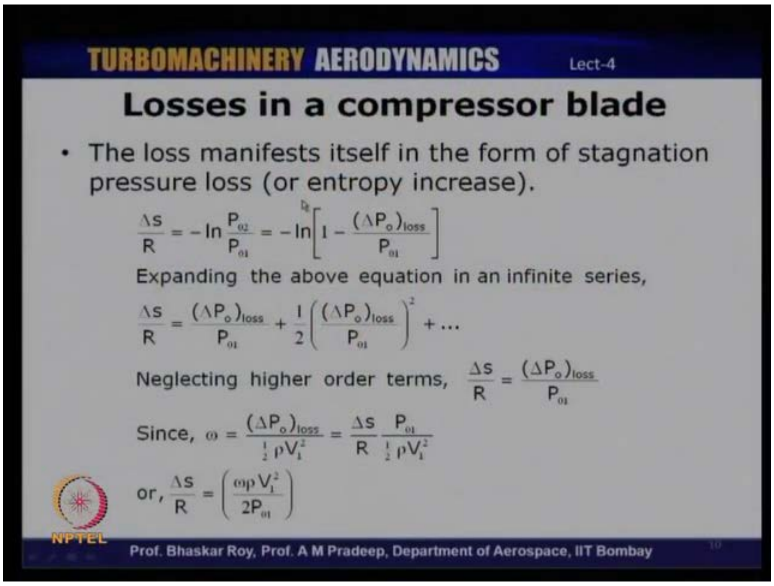

So, the loss that we see toward from a measurements or computational analysis, basically manifest itself in the form of stagnation pressure loss or entropy increase. So, as we know entropy change or entropy increase is related to the ratio of total pressures, so, delta S by gas constant R is related to the total pressure ratio which is minus log P 0 2 by P 0 1 which is also expressed in terms of the total pressure loss, and is minus log of 1 minus delta P naught that is stagnation pressure loss divided by P 0 1. So, this right hand side let us expand that in in an infinite series. So, delta S by R is also equal to delta P naught by P 0 1 plus 1 by 2 delta P naught by P 0 1 hole square plus the infinite series.

Now, if we neglect the higher order term, because these square and higher order terms of delta P 0 is is negligible. What we see is that the entropy change delta S by R can be related to the loss, delta P naught divided by P 0 1. Now, we have already defined total pressure loss coefficient in our cascade analysis that was defined as delta P naught divided by 1half rho V 1 square. Therefore, the total pressure loss omega is delta S by R into P 0 1 by 1 by 2 rho V 1 square or delta S by R is omega rho V 1 square by 2 into P 0 1. So, what we can say is that there is a direct correlations between the entropy rise and the total pressure loss. And they are directly proportional as, we had expected that entropy rise across or the total pressure loss that is encored in an axial compressor; or in any turbo machine for that matter is related to the change in entropy across that is particular compressor blade.

So, this is trying to relate the losses across the compressor, in a thermodynamics sense to the entropy rise across this compressor blade. And so, in general if we if we were to isolate all this different components of losses. The profile loss, the 3-D losses, the shock losses and the mixing losses and so on. The net loss across a compressor or turbo machine, is a sum total of all these different individual components of losses.

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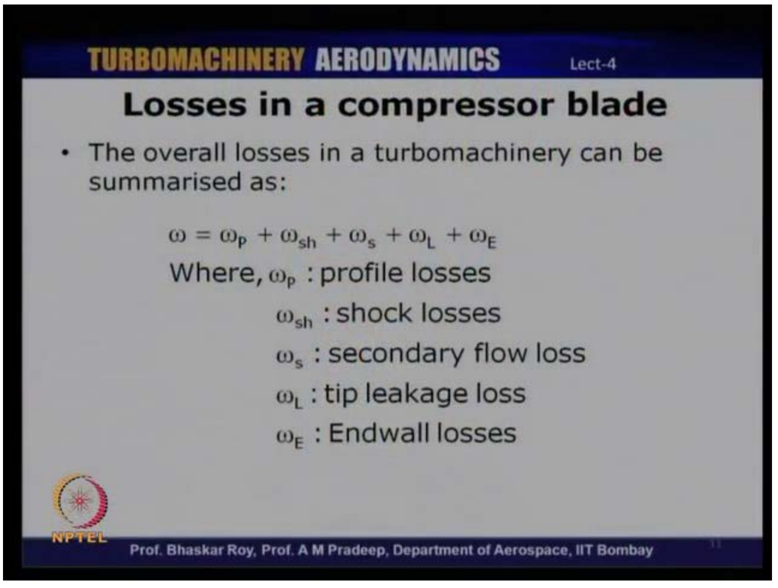

So, the overall loss in a turbo machine can be summarized as the sum of all these different components of the losses. The profile loss, the shock losses which is true only for a transonic machine, if the flow is supersonic and the secondary flow loss or and the tip leakage flow loss. These are of course, 3-D losses and the endwall losses. Of course, this is the mixing loss has been added in the profile loss, has we will see little later. Mixing loss is usually, added to the profile loss itself and we going to estimate mixing losses, the sum total of mixing and profile losses. Empirically by calculating or by estimating the mixing and the profile loss together, let us what we going to do next.

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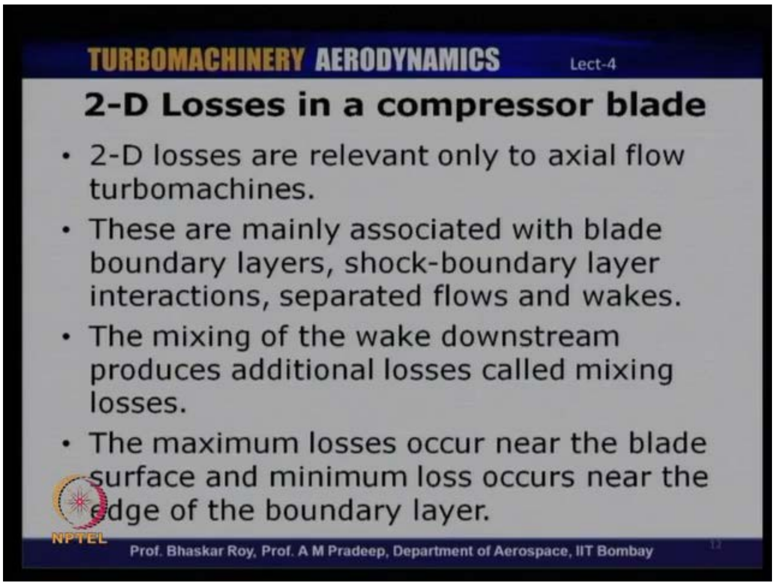

In terms of estimating the losses across a compressor in a 2-D sense by adding up the profile loss and the mixing loss. So, we will take a look at the 2-D losses for the moment and 3-D loss in a separate lecture all together. Now, 2-D loss is of relevance or significance only in the case of an axial flow turbo machine. It is not really true for does not hold much for significance for other forms of turbo machines like, radial or the centrifugal kind of turbo machines. And the the main significance of the 2-D losses is that some of these, can be estimated from a cascade analysis. We have seen that cascade analysis is a simplified form of analysis of an actual turbo machine. Where the flow is assumed and ensured to be two–dimensional and so some of these losses, can be estimated from the measurements that or carried out in a cascade.

So, what are these different forms of losses. So, 2-D losses are mainly associated with blade boundary layers and the shock boundary layer interactions, in the case of transonic machine and separated flows and wakes. And there is an additional component of loss which is incured which is basically, because of mixing of the wake with the (( )) layer downstream of the blade, and that produces an additional component of loss which is called the mixing loss.

Now, it is observed that the maximum losses obviously occur near the blade surface, because that is where the viscous effects are maximum? So, one can and if other 3 defects are neglected, then the maximum losses obviously occur near the blade surface, because of the effect of the viscous viscosity on on the flow itself. And the minimum losses are are expected are found to be further away from the blade surface, towards the edge of the boundary layer itself. Now, let us now classify the 2-D losses themselves. We have classified losses in general, but know let us take a look at, what are the different forms of 2-D losses that we would be interested in.

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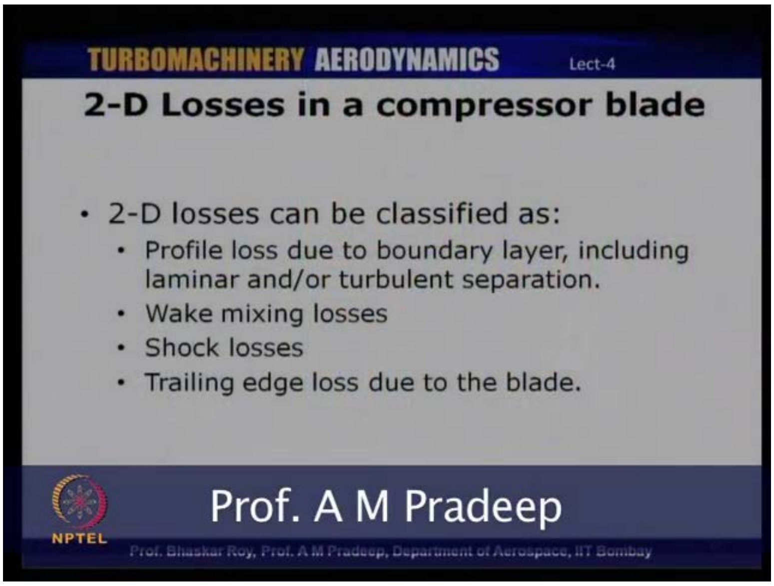

Now, 2-D losses can be classified in terms of these different parameters, one is the profile loss which is basically, because of the boundary layer, which also includes a flow separation which is either a laminar or turbulent separation. One may have wake, mixing losses as we have just know discussed. One may also have shock losses and one might encounter trailing edge loss just, because of the blade itself. So, these are the different forms of losses that one can expect in a two-dimensional sets.

We will first take a look at the profile loss, and then we will now we will derive an expression for empirically calculating profile loss, sum total of profile, plus the mixing loss. Of course, we will not do the detailed derivation here, as it is already given some of these text books, which I explain little later.

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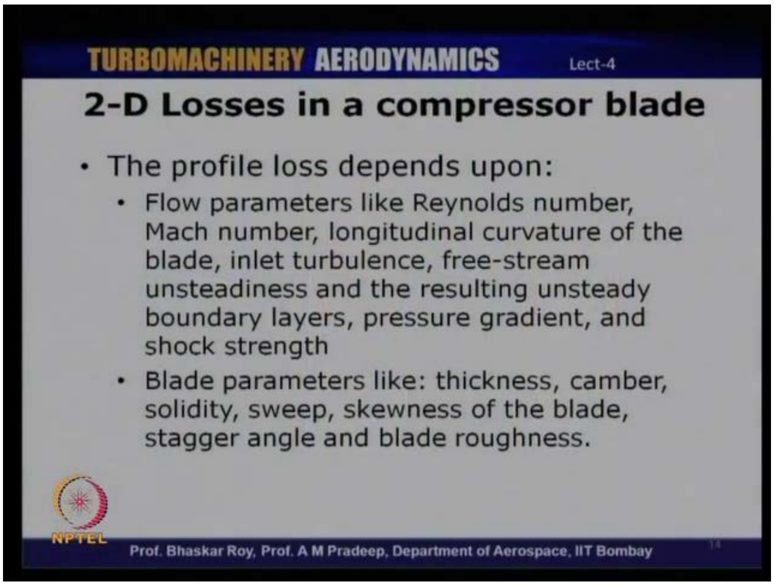

Now, the profile loss depends upon two different sets of parameters. One set of parameter is related to the flow itself, and another set of parameter is to do with the blade itself or the blade geometry. Now, the flow parameter - the different flow parameters which influence the profile loss are the Reynolds number, the Mach number, the curvature of blade, the inlet turbulence free stream unsteadiness and the resulting unsteady boundary layers, the pressure gradient and the shock strength.

So, these are the different flow parameters which are likely to affect the profile loss. And in terms of the blade parameters, the thickness of the blade, the camber, solidity, sweep, skewness of the blade, stagger and the blade roughness. These are different parameters which are associated with the blade itself that can influence the profile loss. So, these are two sets of parameters, which can contribute to profile losses.

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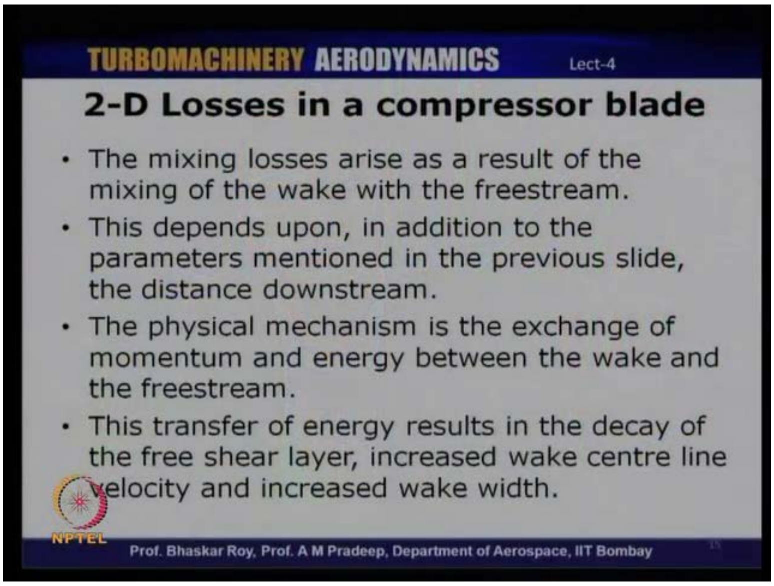

Now, the mixing loss that we have discussed is basically associated with mixing of the wake with the freestream flow, downstream of the blade, trailing edge. And in addition to the fact that is depends upon on just the wake of the blade. It also depends upon the distance at which the measurement is taken. That is if one were to measure the wake, right downstream of the trailing edge of the blade, one might see a very increased level of interaction between the exchange of momentum and energy between the wake and the freestream whereas, if the measurement is taken for downstream of the blade. The exchange of momentum and energy between the wake and the free stream is minimal.

So, basically the mixing losses associated with the exchange of momentum, and energy between the wake and the free stream, and the transfer of this energy results in the decay of free shear layer, and increased central line velocity and increased wake wake width. So, these are all effects of increased missing losses that are likely to be encountered in let us say a cascade experiment that one might carry on. Now, as you proceed downstream further downstream, the effect of the wake mixing diminishes and further downstream one would see a uniform relatively uniform flow, because the effect of wake mixing would have substantially diminish by them.

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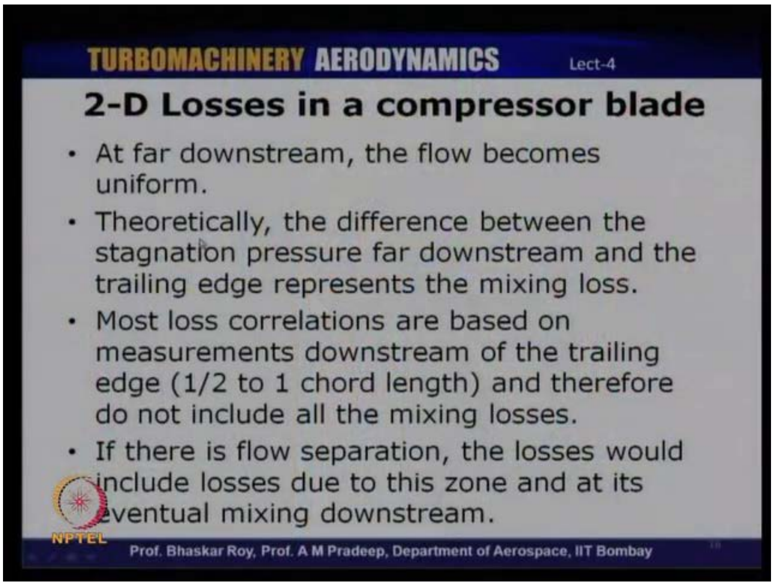

So, which means that at a substantially downstream distance, the difference between stagnation pressure further downstream far downstream and the trailing edge will basically represents the mixing loss; that is if we can estimate the stagnation pressure at a region which is far downstream were the effects of mixing is negligible, and also the stagnation pressure right at the trailing edge of the blade. The difference between this two should theoretically give us the mixing loss.

But what we will see very soon is that most of these correlations which we are going to encounter are based on measurements which are downstream of the trailing edge by half the chord length or one chord length or some distance in between these two. Which means, that we may be missing certain amount of mixing loss, we may not be including all the mixing losses, which one should have which will occur only, if the measurement is taken right of the downstream, right of trailing edge and at a distance which is far downstream of the trailing edge.

And if there is flow separation taking place which may occur at increased incidence angles, then the loss also will include some amount of losses, on account of this additional wake which is generated, because of the flow separation itself. So, mixing losses as I just mentioned, is theoretically estimated if we have the measurements right at the trailing edge of the blade and the difference between this and the stagnation pressure far downstream where the effects of mixing is negligible.

So, let us now, try and estimate and try to derive some expressions for estimating some of these losses. And we will basically be estimating the profile loss, and the mixing loss together, which is a normal practice, because it is not really possible to segregate these 2 components of losses even though, theoretically as I mentioned. It should be possible for us to segregate the mixing loss, if we have of course, the measurements at the exact trailing edge and far downstream.

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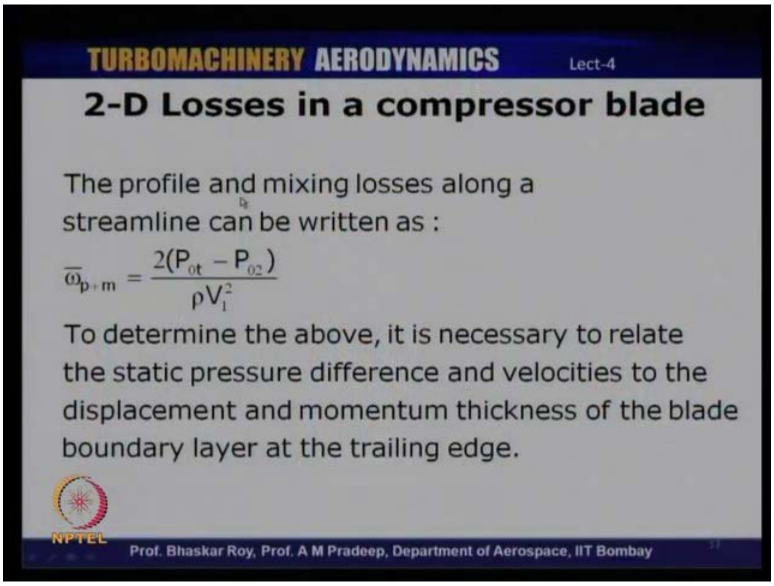

So, the sum total of the profile and the mixing losses along a stream line. We can estimate, as omega bar P plus m refers to profile plus mixing is equal to the difference between the total pressure for upstream or in the free stream P 0 t minus P 0 2, which is the downstream, total pressure divided by the dynamic pressure in the inlet. Now, this is the general expression for the losses itself but, we would like to have an expression, which is related to the measurements in little more detail rather than a generic expression for losses.

Now, if we need to determine, what we have just know discussed written down here, it is necessary that we also relate the static pressure difference and velocities to the displacement, and momentum thickness on the blade boundary layer at the trailing edge. Because the profile loss is basically, referring to the boundary layer effect and the losses on the account of the viscous nature of the flow itself. So, it will be necessary for us to estimate boundary layer thickness, in terms of the displacement and momentum thickness, at the trailing edge to be able to estimate the profile, and mixing losses together.

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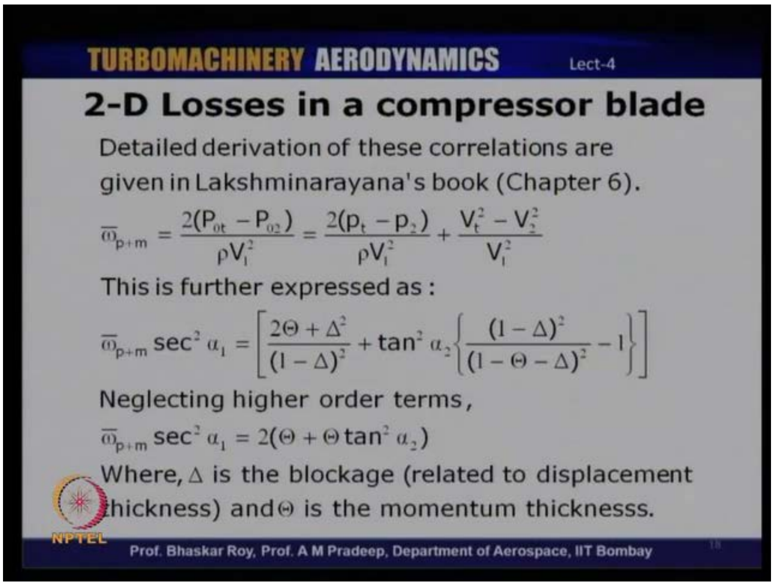

So, there is a detail derivation for what I am going to discuss now, given in the book by Lakshminarayana. So, I would suggest that it is a straight forward derivation which why am not discussing that detail here. So, I suggest you can go through the derivation given in the chapter 6 of Laksminayarana's book. Where, it is shown that the losses, total pressure losses, which I have in general are related to 2 into P 0 t minus P 0 2 by rho V 1 square; can be related to the sum of static pressure difference and the velocity square.

So, this is equal to 2 into P t; which is the static pressure at free stream minus P 2 which is static pressure, at the trailing edge divided by rho V 1 square plus V t square which is the free stream velocity minus V2 square by V 1 square. Now, from this to the next expression which I have written here, is what is given in the book by Lakshminarayana. So, this can be expressed further as the loss component omega p plus m sec square alpha 1. This is equal to this is the alpha 1 is the inlet angle is equal to 2 into theta plus delta square by 1 minus delta the hole square plus tan square alpha 2 into 1 minus delta hole square by 1 minus theta minus delta the hole square minus 1.

Now, here the delta and theta refer to the displacement and momentum thickness. Delta refers to the displacement thickness, which is also an indication of the blockage. Theta is is referring to the momentum thickness, which is directly related to the total pressure loss.

So, if we expand this in series and neglect higher order terms. When the loss expression can be simplified as omega bar p plus m sec square alpha 1 is equal to 2 into theta plus theta tan square alpha 2. So, here what we see is that if we neglect the higher order terms, the loss is directly proportional to the momentum thickness. So, there is no displacement thickness term coming here, if of course, we were neglecting the higher order terms and expanding in that way, the displacement thickness terms actually can fill out.

Which is expected, because if you look at total pressure loss, the main contributor to that is basically the momentum thickness, because momentum thickness, is directly an indication of the total pressure loss taking place in a in a boundary layer. Displacement thickness tells us, what is the kind of blockage, associated with this flow. So, if we were to neglect the higher order terms, one can relate the profile and mixing loss together to the momentum thickness by the correlation that I have just now discussed. So, if we look at the significance of this loss correlation that I have just discussed.

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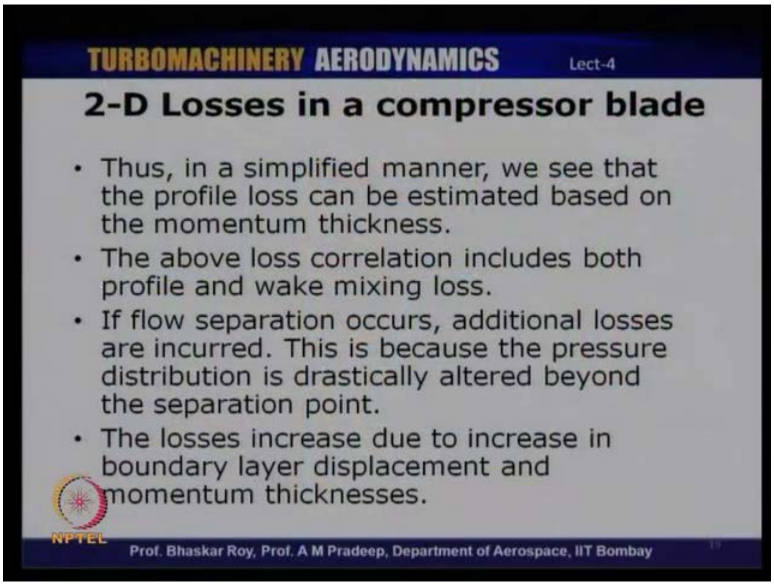

We can see that the profile loss can be estimated simply based on the momentum thickness, and the above loss correlation obviously includes both the profile loss, as well as the wake mixing loss, and the in in the even there is flow separation obviously, there is will be additional losses which are encored this is, because in the presence of flow separation alters the pressure distribution drastically; which is basically true beyond a separation point and therefore, there is an increase in momentum thickness and bound displacement thickness, with flow separation with coming into picture and obviously that leads to an increased over all loss of profile plus mixing losses.

So, presence of flow separation we will only add up to the losses which are over and above, what we have just now discussed for a normal boundary layer. Now, in addition to what we have just now discussed, one may also have certain amount of deviation, taking place at the trailing edge of the blade and we can estimate that based on the momentum and displacement thickness itself. On how the deviation can be estimated based on the change in momentum displacement thickness.

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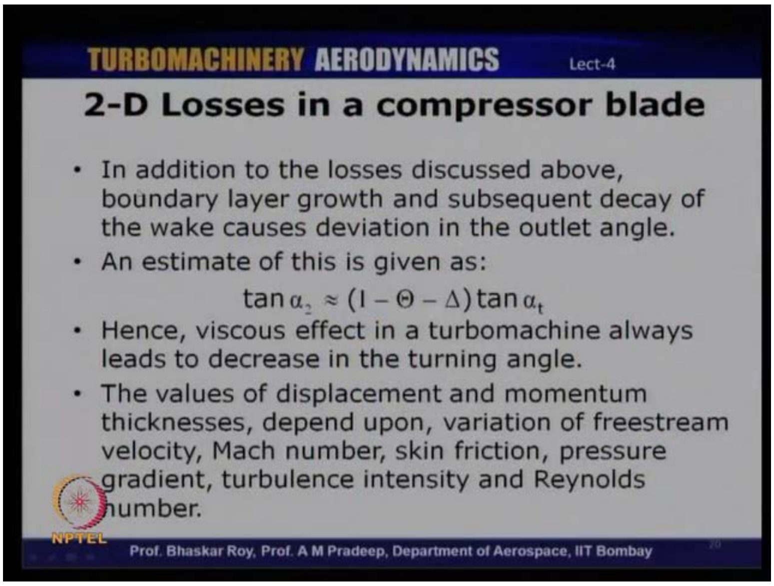

So, boundary layer both and subsequent decay of the wake as we have seen, we will also cause deviation at the outlet of the blade. Which again we can estimate, we have seen that there is component of the outlet angle coming in the last term. So, that can be related to the displacement thickness that is delta and the momentum thickness and of course, the inlet angle. So, 1 minus theta minus delta tan alpha is is basically giving us some indication of the deviation taking place at the exit. Which is of course, an estimate, because there are other terms involved here which have been neglected, because they are higher order terms and the losses in terms of higher orders can be neglected.

Now, what is an implication of this, estimate of the deviation is that viscous effect in a turbo machine always leads to change in the turning angle and it tends to generally it tends to decrease in the turning angle itself. Now, there are different parameters which can influence the displacement at the momentum thickness. Some of them, we have already discussed earlier on like variation of freestream velocity, Mach number, the skin friction on the blade surface, the pressure gradient which is also function of the trail turning, the turbulence intensity and the Reynolds number.

So, these are different parameters which can influence, the displacement and momentum thickness and therefore, in general they can also influence the profile and mixing loss together. So, if we summarize, the discussion on the profile losses one can estimate the loss that is profile plus mixing losses by two different ways. One is of course, based on measurement which we carry from our cascade analysis and the other is of course, to carry out computation and computational an analysis which of course, we will discuss in lot more detail towards end of the course. We have few lectures, dedicated towards discussion on how we can compute flow through turbo machine and losses etcetera.

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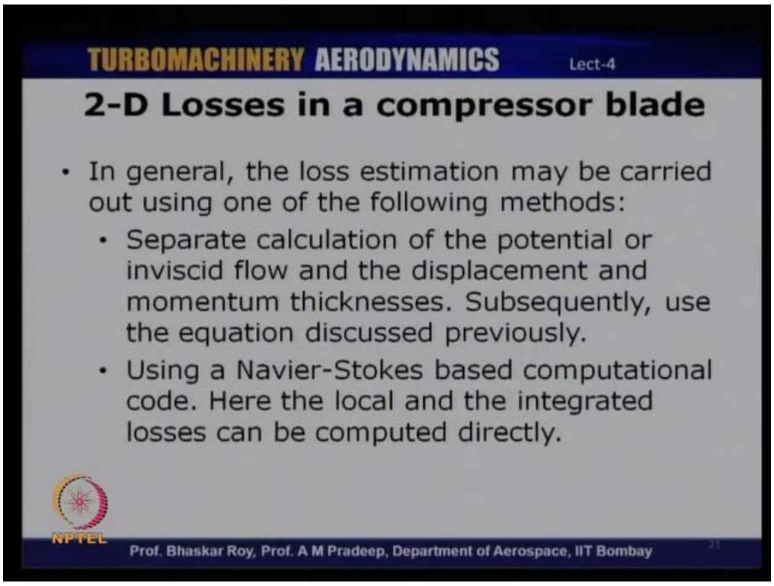

So, there are 2 distinct ways of estimating this; one is by calculating the inviscid potential flow, and also the displacement momentum thickness and subsequently of course, use the data which we have got from cascade analysis, towards estimating these losses. The other method of course, is to use a Navier- Stokes based computational code and here of course, one can get the local and integrated losses, directly without having to of course, segregate the losses. It is still possible to segregate losses but, there are there are uncertainties in terms of how well this computational course can estimate and successfully segregate different component of losses. Some of these ofcourse, issues we will discuss in detail in later lectures.

So, so far we have discuss we have been focusing our discussion on 2 distinct components of losses, the profile and the mixing loss. There are 2 other forms of losses which I mentioned the shock losses and the 3-D losses. 3-D losses, we will discuss in detail separately.

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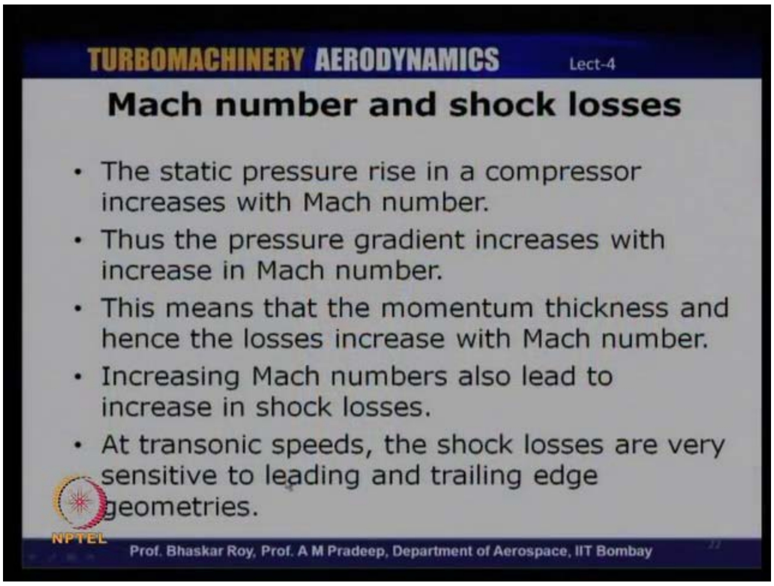

Let us now, take a look at the shock losses and the effect of Mach number, on the shock the loss itself.

Now, there is a direct correlation between Mach number and the shock losses. The static pressure rise obviously, increase there is the function of the Mach number itself. It increases with Mach number, which means that as a static pressure rises, there is an increase in pressure gradient with Mach number. Which means as the pressure gradient increases, the momentum thickness will also increase, because with increase in pressure gradient, the boundary layer is drastically effected as a result of that and therefore, it affects the momentum thickness as well as the displacement thickness. And when momentum thickness increases, it also leads to an increase in losses as the Mach number increases.

On the other hand increase in Mach number also leads to increase in shock losses. Because shock loss is directly, a function of the shock strength and shock strength is directly a function of the Mach number. So, as Mach number increases, shock strength increases and therefore, shock losses also will increases. And of course, a transonic speeds, the shock losses are also besides the Mach number, there are also very sensitive to the leading and trailing at geometries and which is one of the reasons by transonic compressor blade geometry is substantially different from a normal subsonic blade geometry and one of the reasons being that is the losses are directly function of the blade geometry as well as the leading and trailing edge geometries.

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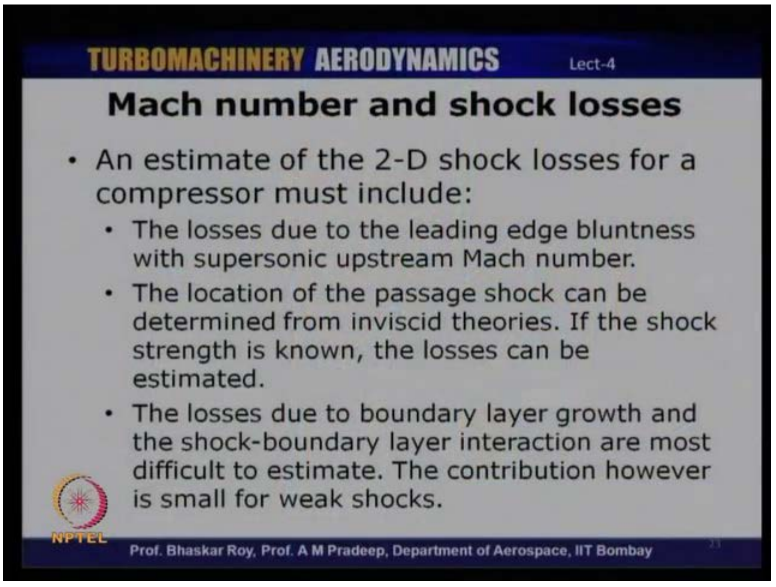

So, if we to estimate the 2-D shock losses in a compressor. One would need to besides knowing the geometry itself, need to know the following that is basically, we need to know the Mach number and its associated parameters. The an estimate for the 2-D losses in compressor will need to include at least 3 of these following parameters. One is the loss due to the leading edge bluntness with the supersonic upstream Mach number.

The second parameter being location of the passage shock, which of course, can be determined from inviscid theories, because shock loss and it is location and easily be estimated from, the gas dynamics that we have that probably have learnt. And once the shock strength is known, the shock losses can be estimated, because shock loss is directly a functional of the shock strength.

The third parameter which is probably the most significant and the trickiest of them is the shock boundary layer interaction that is the losses, because of boundary layer growth and interaction between the shock and the boundary layer is something that is quite difficult to estimate and the no empirical or theoretical correlations, as such which can estimate shock and boundary layer interaction. And this happens to be continuous to be an area of research for many people; how work in the area of the shock boundary layer interaction on how one can accurately estimate and predict shock boundary layer interaction.

And of course, needless to say for weak shocks the interaction between the shock and boundary layer is minimal and therefore, the loss contribution is also minimal. However, as a shock strength increases, the corresponding shock boundary layer interaction becomes quite significant, and estimating that becomes even more critical and tricky. So, these are 3 different parameters that one, we need to take into account when one is trying to estimate shock losses in at least two-dimensional sense. The strength of the amount of losses of course, depends upon the shock strength which again is a function of the Mach number and geometry.

Now, let us now, take a look at one of the empirical correlations amongst many others which are have been kind of been proposed over many years now, and is been widely use to estimate the shock, the losses, total pressure losses associated with the shock in a transonic compressor. And this is an empirical correlation which has been successfully used and validated with the experimental data.

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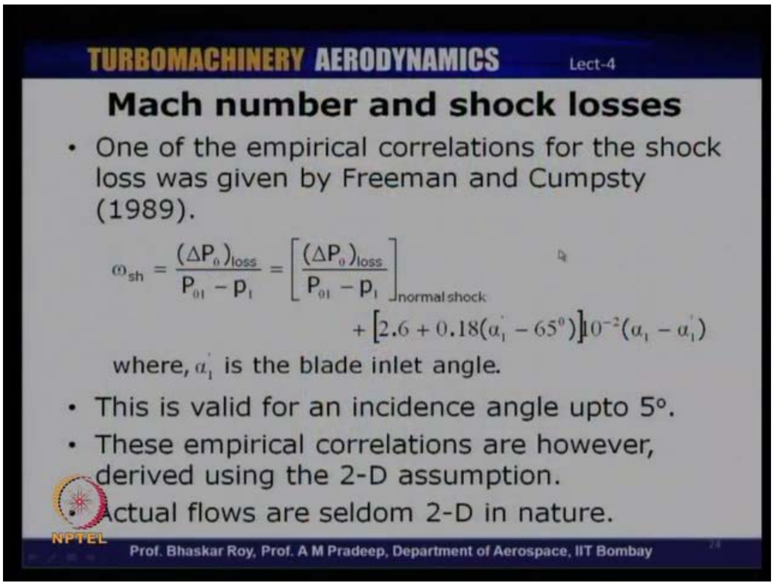

Of course, this was proposed long back by Freeman and Cumpsty in 1989, and the shock loss is basically, a function of the total pressure loss which they have correlated is to a normal shock plus an empirical term here. So, delta P naught loss is the stagnation pressure loss across the shock divided by P 0 1 minus P 1 which is static pressure; this is basically for an normal shock plus an empirical term here, 2.6 plus 0.18 into alpha 1 prime minus 65 degrees, and multiplied by 10 power minus 2 into alpha 1 minus alpha 2 prime; where, alpha 1 prime is the blade in that angle. So, here this difference between these two tells us the incidence.

So, this is basically valid for very low incidence angles and it has been seen that it is reasonably accurate up to what an angle of 5 degrees, and as incidence exceeds 5 degrees and the prediction of shock loss is going using this correlation is not very accurate. Of course, these are correlations which have been derived using the two-dimensional assumptions and as we know that actual flows are seldom to two-dimensionally natured, which is also true for the other loss components like, profile loss and mixing loss most of these which have been estimated here, are with the assumption that the flow is necessarily two-dimensional.

So, the presence of three-dimensionality or three-dimensional flows will only complicate the losses and which is why we have devoted a separate lecture, altogether which discusses purely the 3-D flows, the tip leakage flows, and the secondary flows. So, the shock loss correlation that I have shown here is just one of the many correlations which are available. This is one; which has been validated and widely used for estimating, the shock losses in a transonic axial compressor.

So, let me now, quickly recap our discussion in today's lecture. Where, we discussed 2 distinct aspects; one was to do with the cascade analysis and performance parameters which we can derive from a cascade analysis. We discussed about 2 distinct parameters; one is the total pressure loss coefficient and the other is the static pressure rise or C p. Total pressure loss is an indication of the losses taking place across the cascade and the static pressure rise or C p distribution gives us some indication of the loading of the blade. And these are the 2 common parameters which one can derive from a cascade - a simple cascade analysis.

The second part of the lecture was discussion on losses, we classified losses in general as profile loss, mixing loss, 3-D losses and also the shock losses associated with transonic compressor. Out of all these we have devoted today's lecture towards discussion on 2-D losses and I discussed 2 distinct components of these losses; the profile plus mixing loss and the shock losses in general.

So, it is possible for us to empirically estimate these losses based on certain correlations, which I have discussed today and these are empirical correlation which can make use of data which one obtains from cascade analysis, and one can estimate losses taking place in a particular cascade geometry using the data that is obtained from the cascade study. And also try to segregate losses in terms of profile plus mixing as one component, and raw clauses as a separate component.

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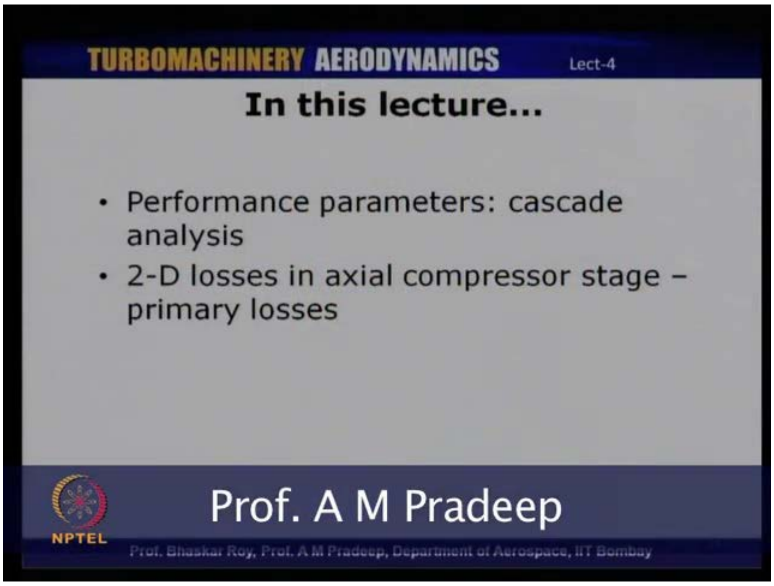

So, these are the different aspects that we had discussed in today's lecture. Performance parameter from cascade analysis 2-D losses in compressor stage basically, focusing on the primary losses. And in the next lecture, what we will do is to take up some problems for solving, we will basically have a tutorial session in the next lecture.

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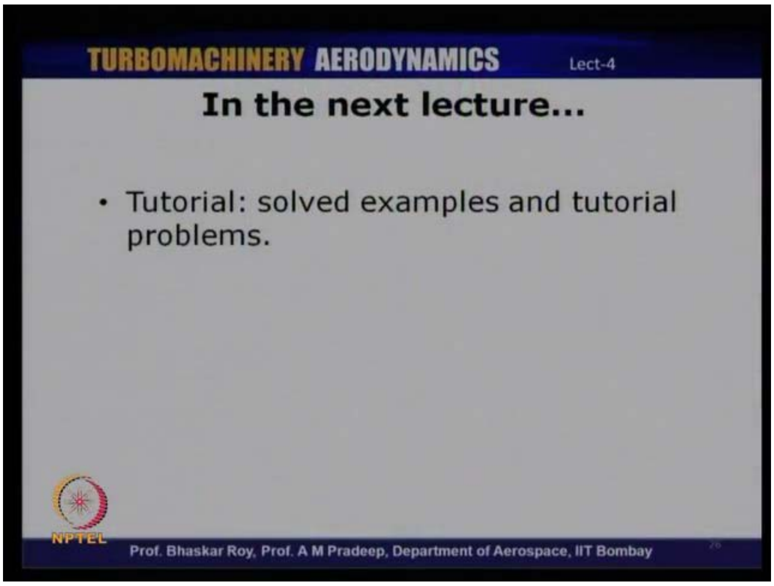

We will solve a few problems, and I will also leave a few problems for you to solve as tutorial exercise problems. So, this is what we will we taking up for discussion in next lecture.