Jet Aircraft Propulsion

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Lectrue No. # 15

Cascade Analysis; Loss and Blade Performance Estimation

Hello, and welcome to lecture number fifteen, we are on the fifteenth lecture of this lecture series on jet aircraft propulsion. I guess by now you might have got some idea about what this course is all about; of course, we had given lot of introduction in the first few lectures. And we are probably almost half way through this lecture series, wherein we have been discussing a lot about what are the different types of cycles that are used in jet aircraft propulsion; how is it that we can analyze a jet aircraft engine cycle thermo dynamically.

We have looked at the basic thermo dynamic cycle, the ideal cycle of jet aircraft engines, then, what are the component performance parameters that can be incorporated; and of course, the real cycle analysis of jet engines. Now subsequent to all these discussion, we have initiated our detailed discussion about different components of the aircraft engine; and in the last lecture, we have discussed about the compressors.

Now, compressors are one of the probably, one of the most important components of jet engine of course, all the components are definitely important; compressor is one of the most more important components of a jet engine. And we have initiated some discussion on how we can analyze a compressor, and what are the different terminologies used in compressor design and its analysis; and what is the simplistic way of analyzing a compressor.

So, we have initiated the discussion on 2D - two-dimensional basis, wherein we have discussed about one cross section of the compressor trying to look at the rotor and the stator combination that is the stage of a compressor, and how we can go about some preliminary analysis of a certain rotor and the stator combination.

Now, during this discussion we have discovered that for such an analysis, it is necessary for us to get the velocity triangles; velocity triangle is basically a combination of vector representation a vectorial representation of the different components of velocity in an axial compressor. Now, in an axial compressor as you know in the rotor especially, because of the very fact that the rotor has a rotation, a tangential component of blade speed, a peripheral speed associated by that; that results in the incoming velocity to take up two different velocity components; that is, if an observer were to stand outside the rotor and then see what is happening, then he sees a certain velocity.

Now if the same observer is actually sitting on the rotor then, because of the fact that there is a relative motion between the rotor and the incoming flow, there is a different velocity which the observer would see.

So, these are velocity components in different frames of reference and so this basically constitutes a velocity triangle; and so fundamental design and analysis of compressors begin with the velocity triangle, so I am I guess you would have understood how to construct a velocity triangle from our discussion in the last lecture; and also, how is it that velocity triangles can help us in a better understanding and design of axial compressors.

Now in today's lecture what we are going to discuss is the slightly different topic of course, it is still related to compressor, but it is probably on a more simply simpler level, because we what we going to discuss initially is something to do with the stationary row of plates like a stator; so in today's lecture we are going to basically talk about what is meant by cascade.

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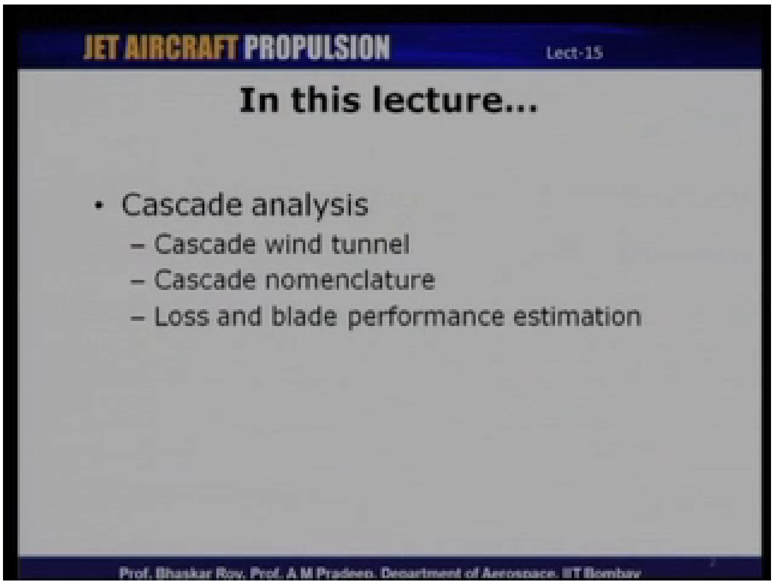

So we will begin our analysis our discussion today on cascade analysis, what we mean by a cascade? We will take a look at what is a cascade wind tunnel; and then we will also try to understand the nomenclature associated with a cascade, there are lot of angles and velocity components and other geometric parameters which are involved, we will discuss about that during the cascade nomenclature. We will then talk about what are the different losses that probably we can detect or determine from the cascade analysis, and how we can evaluate the performance of a given blade; so these are some of the topics that we are going to take up for today's discussion.

Now let's first understand what is meant by a cascade; and why is that we should be discussing about a cascade? Now cascade at least, literally it means a series of certain things; we have probably you must have when you have read certain books or magazines you must have read about this phrase of cascading effect and so on, wherein its basically meant that a series of certain event is repeating, and it carries on.

So that is the fundamental literal meaning of cascade, and in this context that we are going to discuss today its probably in some sense the same thing, because cascade in our terminology here refers to a series of blades which are arranged in a certain repetitive fashion; and the cascade is basically a series of stationary blades.

So you might wonder why we should be even bothered about a set of stationary blades, and how does it help us in our analysis of compressors, which primarily cons comprise of rotors and then of course, there are stators.

So how can we gain any beneficial information from a series or set of stationary blades; well, that is not really true, because cascade does play a very significant role in our understanding of compressors, and the performance and behavior of a series of blades.

So basically the idea of a cascade is that, if we have a set of blades, which are arranged in a certain fashion, which is how it would be in a compressor but, just that in a compressor the blades are usually arranged along on a disc, and on a shaft basically, where as in a cascade in a linear cascade, blades are arranged in a straight line in a one plain, where as in a rotor or a stator the blades are not really arranged in a stationary in a linear fashion, but its arranged on a rotary frame.

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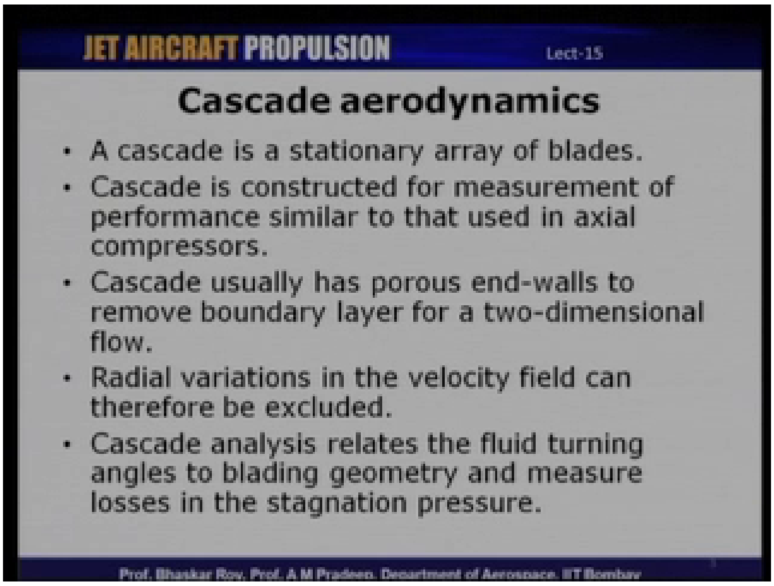

So, that is one of the differences between a cascade and of course, the actual blades so what is the basic requirement of a cascade, we will basically a cascade is meant to understand or give us some better understanding of a set of blades, which are used in a similar fashion to that of a of compressors, but in a much more simplistic fashion.

Now, you have so, that the idea of using cascades was developed long ago in the early days, when compressors were actually being developed and designed in the initial stages, may be sixty years early or sixty to seventy years early around. So it was probably, in the early thirties of nineteen forties that, cascades came to be a of use for very simple testing and analysis of compressor in fact, even a cascades are used to even for turbines, but today we will discuss about compressor cascades.

So it was long back that, these test methods were developed; and they have been used ever since its still being used very popularly even today, but the difference between the significance of cascades today, and what it was forty, fifty years ago is different in the sense that, in today's technology, lot of significance is also given to numerical analysis or computational analysis.

So, with the development and use of computational tools, like computational fluid dynamics so, the significance of cascades probably has been slightly lower than what it was many years ago but, it does have it does have a lot of significance, because there is lot of uncertainty even till date, on some of the data you get from a computational analysis; so cascade is still used for validation of some of these computational tools.

So, as I mentioned cascade consists of a series and array of blades which are arranged in a certain fashion; and they are these blades are representative of the blades, which would be used in a actual compressor; the difference is that usually cascades have blades, which are two-dimensional, which means that they are like air foil sections, which are extruded infinitely, unlike an axial compressor, where the blades are not necessarily two-dimensional, where the blades may have a twist and the blades can take three-dimensional shapes, this is not true for a cascade.

And so, to ensure that, the flow is two dimensional in a cascade, what is done is basically that, we should ensure that, the end walls of the cascade does not have boundary layer effects; and therefore, most of the cascades usually have end walls, which are porous or there is a provision provided for removing boundary layer, and that ensures that, the flow entering the cascade is two dimensional.

One of the most important distinguishing features of a cascade is, because it is now two dimensional, we can safely ensure or exclude radial variations in of the properties that is radial variations of a velocity and pressure and so on can be safely excluded, because we have ensured that the flow entering the cascade is two dimensional; and since the cascade blades themselves are two dimensional; this will safely ensure that, we can live out or exclude radial variations of different properties.

So, what is basically cascade do? cascade basically relates or tries to give us some information in fact, a lot of information on how does a given set of blades behave in terms of the pressure rise that is on the blade surface that is the Cp distribution, static pressure distribution on the blade surface, as well as, the losses that are encountered on in total pressure because of frictional effects and so on; that is at the trailing edge of these blades; and how does these parameters change for a given turning of the blades.

So we have for example, if I am to design a new series of blades, which are to be used in an actual compressor; now, one of the ways of course, to do that is to design the blades, fabricate the blades as it is, and then test them in a actual (( )) but the amount of time and in fact, effort and of course, the money that is required for testing actual compressor blades in actual geometry is substantial; and therefore, we would like to first take a look at a simplistic analysis, which can tell us, whether the blade is likely to perform well, when it is actually implemented on a compressor.

So, cascade is one such way, where in we can get very quick results, very quick turnaround from the experiments, by very simple experiments, but at the same time, they give a lot of insight into the performances of these blades. So, cascade analysis can give us, how the blades are going to perform, as you keep changing the inflow angle that is known as incidence, which you will define little later, how does the blade perform as you keep changing the incidence angle; and what is the total pressure loss that, this kind of a blade geometry is going to give us.

So, these are some of the information that, cascade analysis can give us, and that plays a very significant role in a detailed design analysis of compressor blades; so it is necessary that we first have a simplistic and a quicker experiment, which can give us a lot of details, and that can help us a lot in our understanding of the performance and behavior of these blades.

So, that is one of the aspects or beauty of cascade analysis; so, a cascade basically consists of as, I said a series of blades, and these blades are usually mounted on a turn table that is, these blades are as I will show you little later that these blades, which are arranged in a certain fashion, they are mounted on a turn table, which means that, the whole set of blades can be rotated about a given axis, and so as you rotate these set of blades, you are basically changing the incidence of the angle, at which the flow is actually entering the cascade.

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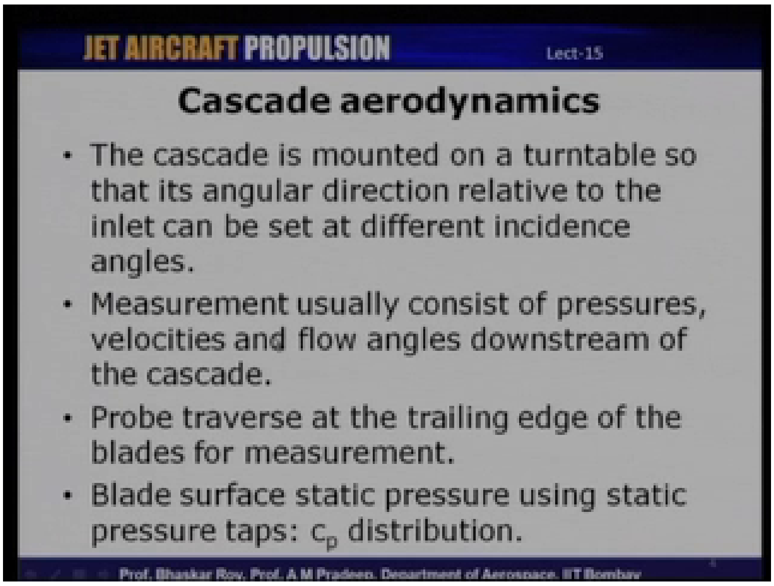

So, you can change the incidence of these blades, because the blades have mounted on a turn table; and what is that, we measure in cascades measurement usually consists of pressures, of course and then velocities, and flow angles downstream of the cascade. Besides of course, these fundamental properties nowadays, we also end up measuring the boundary layer properties, the skin friction and lot of other measurements, can also be done in a cascade; but fundamentally cascade analysis or measurements usually consists of pressure, velocities and flow angles; and these are usually carried out by moving or traversing a probe at the trailing ends of these cascade blades.

And, on the blades surface, what we basically measure are, the static pressures on both the suction surface, as well as the pressure surface; and these cascade blades, when they are fabricated or manufactured they usually have these pressure taps embedded on the cascade blades; so pressure taps mounted or embedded on the a blade surface will help us in giving us some idea about the static pressure distribution on these blades, because the Cp distribution gives us a lot of information about the loading of the blade that is, how much force or how much work can this blade do on the flow; and so that is obviously an indication of the pressure arise, which the cascade can cascade can basically give us.

So, all these simple information, all these fundamental information, which of course, form the basis for every detail analysis can be obtained from a cascade analysis. So, let us now take a look at a typical cascade wind tunnel, so we will now appreciate what is cascade all about, because I till now I have just been talking about cascade being a series of blades and so on. So, let us take a look at wind tunnel, a cascade wind tunnel and see, what are the different components, which constitute a cascade wind tunnel, of course, there are different types of cascade wind tunnels; we will see one of the types of cascade wind tunnels which are commonly used.

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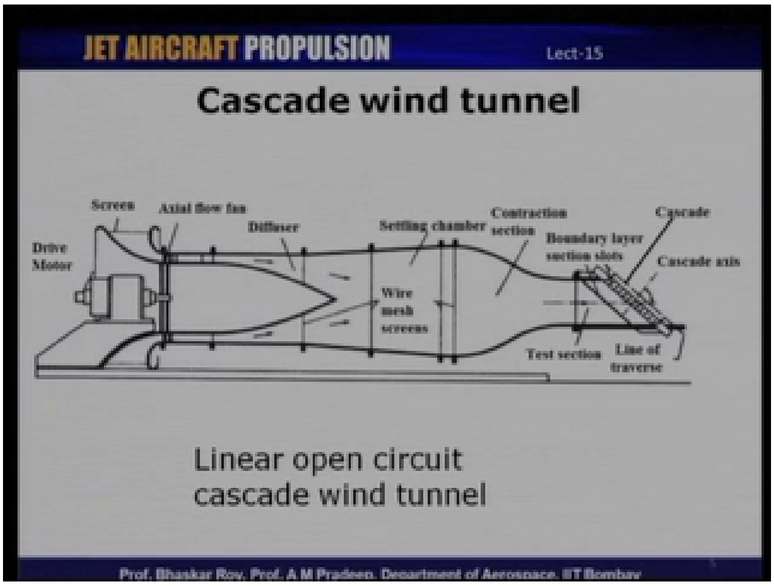

Now, this wind tunnel, which is shown in this picture, here is a linear wind tunnel; it is a linear wind tunnel, because the blades are arranged in a linear fashion; you can see here, these are the cascade blades; I mentioned initially that, cascade blades basically consists of the blade, which are arranged in a linear fashion. So, these are the blades, which are arranged in a certain fashion, self similar blades and since they are arranged linearly, it is called a linear cascade; there are also annular cascades, where these blades are arranged in an annular fashion, which basically represent a state of blade; and the other parameter that is mentioned here is linear open circuit cascade.

Now, open circuit means that, the flow is sucked in from the atmosphere and exhausted through the cascade; that the flow is not recirculate there are also wind tunnels, which are known as closed circuit wind tunnels, wherein the same flow will enter into a loop and then, it is circulated within the test section and the cascade. So, this is known as, in such a case that is known as an closed circuit cascade; here, its called an open circuit, because the ambient air is sucked in and then it is exhausted; it is not the same air, which is continuously recirculated.

So, what are the different components, you can see here, there is a motor; this is the motor that is shown here, this motor is driving an axial fan, which generates the required mass flow for the cascades; so this fan is driving a certain mass flow, which is what basically passes through the cascade. Now, the fan sucks in air from the ambient through a set of screens, because we would like the flow to be a smooth as well as, to eliminate the possibility of some foreign objects getting heating on the fan and damaging it.

So, there usually would be a set of screens before the fan; and then, after the fan, we have a diffuser, which builds in the static pressure required, and then there is a settling chamber; and also, you can see there are lot of wire mesh screens; so all these wire mesh screens basically are meant to brake down larger (( )) in the flow, reduce the turbulence in the flow, because the fan, they exhaust from the fan is effectively high turbulent flow, so you would like to decelerate it, at the same time, you would like to eliminate any possible turbulence, which is still present in the flow.

So, turbulence is reduced, as it passes through these wire mesh screens; and so this is basically known as the settling chamber, where the flow or velocities are reduced, and so you have a buildup of stagnation pressure here, of course, it is still not stagnant, and then at the end of the settling chamber, we have a contraction; contraction is like a nozzle, a subsonic nozzle, so there is a reduction in area, which means that, because it is a subsonic flow as it passes through the contraction section, the flow will accelerate and as it accelerates, because it is an accelerating flow, there is also a reduction in the turbulence.

So, turbulence reduces and so, at the exit of this contraction, which is, where the test section begins, we have a relatively very smooth flow, which has a very low turbulence; and at the same time, we have a uniform a velocity profile, which enters into the cascade that is very important, because you need a very uniform velocity profile entering the cascade, because we need a profile, which is known a priory it should not be an arbitrary velocity profile.

So, cascade is shown here, we have these blades, which are arranged in some fashion, which I will explain later on; and then we have, what you can also see here, mentioned as boundary layer section slots, so there is a slot just before the cascade, which is known which are known as boundary layer, which there could be multiple slots there; these are meant for removing boundary layer fluid from the end walls of the cascade. You would like to remove the boundary line fluid, because the flow entering the cascade needs to be two dimensional; and that can be ensured only when we remove boundary layer from the end walls; so that is carried out you see in boundary layer suction slots, and so that is basically meant for removing boundary layer.

And then, at the exit of the cascade, and the trailing edge, there is a provision made, where in you can move a probe that is, you can traverse a probe at the exit; so that is known as the line of traverse; and of course, this location of this traverse can be changed, it can be at different (( )) from the trailing edge of a blade; so this is basically known as the line of traverse, where in the probe is moved, and you can get lot of data from inter verses stagnation pressure velocity etcetera.

So, this is basically a cascade, want form of a cascade, there are other forms of cascades like annular cascades, close circuit and so on; we will not go into details of that, of course, you will be able to get more information on such cascades in other text books and other research papers.

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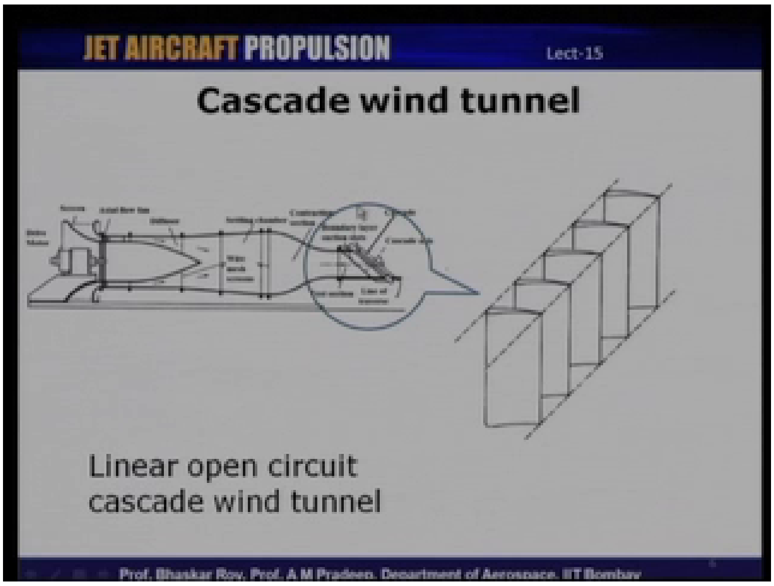

Now, let me take a closer look at the cascade, which have a (( )) about, so if I were to exploit this particular region that the cascade, as indicated here, what you see would be a set of blades arranged in this fashion. So, these are compressor blades, it could also be turbine blades arranged in a linear fashion and that is, why it is called a linear cascade wind tunnel; now, there are wind tunnels, where these blades are arranged in on an annular very similar to that of stator blades, those are known as annular cascade tunnels, but they are very rare; usual cascade tunnels are linear in nature that is, the blades are arranged in a linear fashion.

Now, in this cascade that we have just mentioned, most of the cascades will have the blades, which are fixed at both the ends; that is, there is no tip clearance at any of these ends; but, there are also cascade tunnels, where there is a small gap provided at one of the ends; so that you get a more realistic approximation of rotor blade, because is the cascade were to be fixed at both ends, then it is just like a stator, because it is stationary and it is fixed at both ends. But, if it is a rotor, there has to be a clearance between the rotor tip and the casing, which can be achieved, if you can fix the cascade blade at one end and live a gap at the other; and some of the more complicated cascade tunnels also have a provision for creating a relative motion at the tip.

Now, if you live a certain gap at the tip, it is possible that, we can also ensure that, the casing or the end wall has a relative motion; and that is done by providing, what are known as moving belts that is, you could have a belt at the cascade tip, let us take a look at this at this end, let us say, if instead of fixing the blade here, we keep the casing, a little further up, and also we provide a belt here, which can be continuously rotated; what happens in this case is that, now, you have a cascade blade, which means you do not have to rotate the blades, you just have to rotate belt, which is at the tip of the cascade; and then, there is a gap between the belt and the cascade blade; so that, there is also a relative motion that is present at the tip of the cascade.

So, these are more complicated complex geometries of cascades, which are often used; but some of the simpler ones do not have any such provision, there does there will not basically have a tip clearance, they would also not have a moving belt; so those are simpler, more conventional forms of cascade tunnels; some of the modern ones, the recent ones have these provisions, where you can provide a tip clearance, you could also provide a moving belt so that, there is a relative motion.

So now, that you have understood a cascade tunnel, what it looks like, and how cascade blades are mounted on a wind tunnel; let us now go a one step ahead, and define the different geometric parameters, which are used in a cascades; so there are lot of angles and velocities and other geometric parameters, which are involved, which are used in cascade terminology. So, we will define some of these terms, the various terms, which are used in cascade analysis; and then, we will go ahead further, and then see, what is that we can do with all these information that we get from a cascade analysis.

As, I mentioned cascade test give us basically, the velocity components, the pressure that static (( )) pressure and also the flow angles, how much the cascade blades can turn the flow; so these are some of the information that, cascade testing can give us, and no doubt that, we make use of these data, we need also, we familiar with some of the terminologies that are used in cascade wind tunnel.

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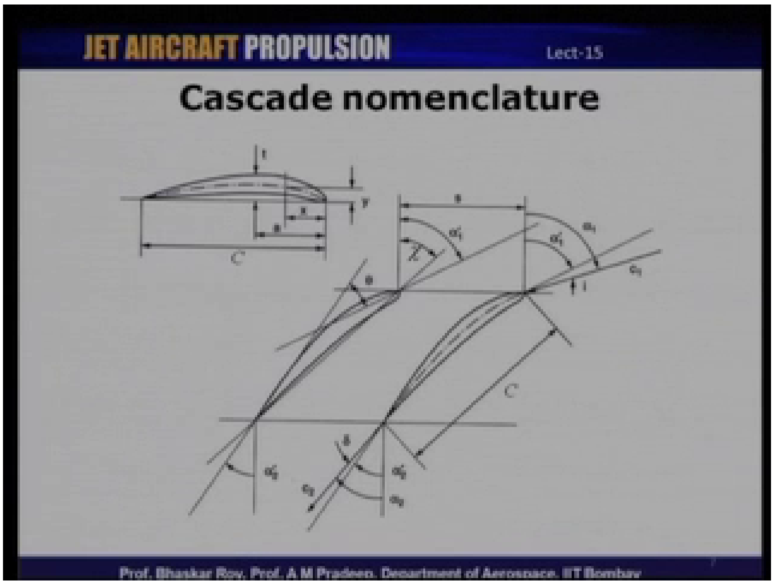

So, let us take a look at, how we can define a cascade, what are the different parameters, which are involved here; so what do you see here is, a relatively complicated picture, but I will simplify that for you; a lot of angles and velocity components, which are shown, but they are some of them are repetitive, in the sense that, what we defined at the inlet or leading edge of the blade is also true for the trailing edge.

So, this is a typical air foil that you can see here, I am sure you must be familiar with some of the air foil terminologies; this is defined as the chord of the air foil; so it is shown here as c that is the chord of the air foil, in this case, it is a blade; and then, the air foil, most of the air foils, which are used, would have a certain camber, it will not be a symmetrical air foil, usually these air foils will have a certain camber.

And so, we know, how to define a camber, so this line that is shown here is known as the camber line; and then, there is a max thickness for these blades, and also the maximum camber at a certain locations; so mac camber achieves a maximum at a certain locations, the thickness achieves a certain maxima; so, those I am sure you would have a studied this, when you had some courses on air foils. Now, if these blades were arranged in a fashion that is shown here, these are blades, which are arranged in a fashion similar to that, it would be in a cascade; so, I am showing here two blades, we in a cascade typically, there would be multiple number of blades, which are arranged in the same fashion, there is self similar blades.

Now, let us take a look at the inlet, at the inlet, we have a certain velocity approaching the cascade blades; we have, I have shown it here by c 1, which is the inlet velocity and c 2 represents the exit velocity. And here, we have an alpha 1, which is basically the angle, at which the velocity approaches the cascade; and alpha 1 prime, that is shown here is basically the blade inlet angle, because the there is no rotation for these blades, these are basically also equal to beta 1, which we have defined in the last class.

So, the angle, at which these blades have been designed for the blade, in that, angle is basically the alpha 1 prime; the actual angle, at which the flow is approaching the cascade is let us say alpha 1, which means that, there is a difference between alpha 1 and alpha 1 prime; so this angle, which is indicated here as I is alpha 1 minus alpha 1 prime, so that is known as the incidence angle. So, incidence angle is basically the angle of attack, as you would have learned in, when you had studied aerodynamics of air foils; the angle, at which the flow is actually entering the blade, which may or may not be the same as the blade in that angle; so, if it is different, it means, there is a certain incidence, which could either be positive or it could be negative.

So, if alpha 1 is greater than alpha 1 prime, then we have a positive incidence and vice versa; and similarly, at the exit, we have c 2, which is the exit flow velocity living the blade trailing edge at an angle of alpha 2; and the blade outlet angle is, let us say alpha 2 prime; so, alpha 2 and alpha 2 prime may not be the same, just like, we had an incidence at the inlet, if they are different it means that, there is a certain deviation.

So, at the exit, we have a certain deviation, which is represented here by delta; so deviation is basically equal to alpha 2 minus alpha 2 prime; so we have incidence, we may have incidence at the inlet, and deviation at the outlet. So, I mentioned initially that, cascade blades are mounted on a turn table and as you rotate the turn table, we can change this incidence angle; we can set the incidence at angles, which are desired and then, we can see how these blades perform, as you keep changing the incidence angle.

So, we change an incidence, the performance of the blade changes and that can, that is one of the aspects, which can be studied using a cascade testing; now, these blades are separated by a certain distance, which is shown here as letter s that is the spacing between the blades; and you can see here two more angles, one is defined or denoted by symbol psi, and the other is denoted by theta; so, theta is basically the angle between tangent to the trailing edge, and tangent to the camber line at the leading end.

So, this is the camber line, which is shown here by dash and dots; so, if you draw a tangent at the trailing edge, and tangent at the leading edge, they both meet and intersect at certain angle; so, this angle, which is represented by theta, is known as the camber angle of this particular blade. So, cascade blades will have a certain camber angle and that is, the angles subtended by the tangent to the camber line at the leading edge and the trailing edge; and then, the angle, which is shown here as psi is basically the stager of the blades that is, these blades are set at a particular angle; so, stager is sometimes also referred to as the setting angle; and this is the angle between the chord line, which is shown here and the axis of the cascade, so, this basically is the axis of the cascade.

So, angle between the chord and the axis of the cascade is the stager angle; and so, again as we mount the blades on the cascade blades cascade turn table, it can be set at a desired angle; so we can also change that, and that is basically known as the stager or the setting angle, at which these blades are set with reference to the cascade axis.

So, these are the different terminologies used in cascade analysis and some of them we have already seen in the last class, when we are talking about velocity triangles that is the blade inlet angle and outlet angle and so on; so, the inlet angle that is shown here is basically, what we are discussed in the last class; but in this case, if the blades are stationary, if you have only one angle, there is no relative velocity here; and that is why we just have alpha at the inlet and outlet, which is basically the blade angle, which is what we are denoted by beta, and in our previous class, but that was with reference to a relative velocities.

So, since there is no relative velocity here, we just have an alpha and so, incidence is the difference between the angles, at which the flow is actually entering the blade to the angle, at which the blade has actually been designed for at the inlet. Similarly, we have the deviation angle at the outlet difference between the angles, at which the velocity actually lives the trailing edge to the angle of the blade at the trailing edge that is denoted by delta.

So, cascade basically has all these different terminologies that will define some of the geometric parameters, and from these parameters, it is possible for us to also calculate certain other performance parameters, which we will discuss shortly; so, as I mentioned cascade, measurements in a cascade will consists of measurement of pressures, velocities and flow angles, and from these measurements, it is possible for us to infer some information about the performance of these cascade blades.

And, in cascade testing, we normally use certain special probes, which are used to measure these exit total pressures and the angles and as well as the velocities; on the blade surface, as I mentioned, we use static pressure taps that is as the blades are fabricated or manufactured, in that time certain pressure taps are embedded on the blades surface and the suction surface and the pressure surface; and then, static pressure can be measured through these pressure taps.

Whereas, the trailing edge of the blade that is, where we measure the total pressure and that the velocities and flow angles, normally we use certain special probes, which are traversed and moved along the trailing edge of the blade, to gather information on these parameters; so, for this purpose we use certain special probes, which are known as claw probes or cobra probes and so on; I will not probably go into details of them in this particular lecture.

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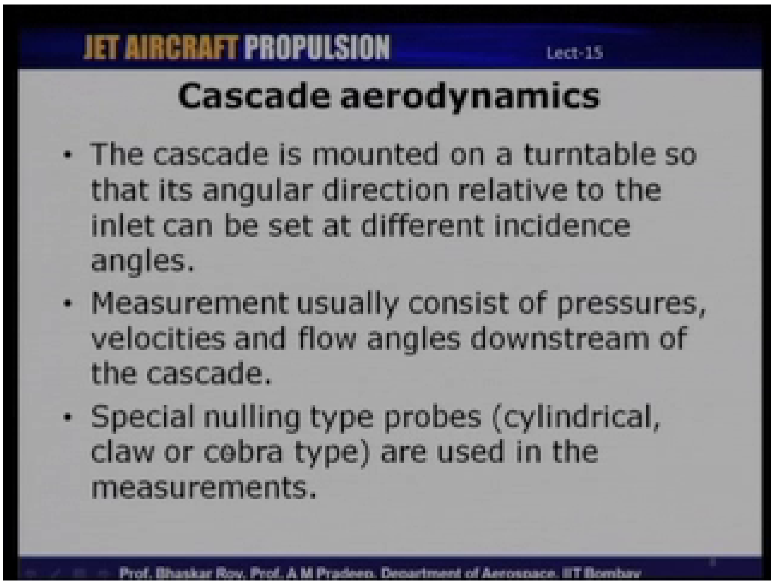

So, special probes, which are known as nulling probes are used in at the exit, if we need to measure the angles as well, they could be of different forms, they could be cylindrical flow type or cobra type etcetera; and you can get more information on these types of probes in most of the text books, wherein we talk about cascades; and so, the measurements usually involved rotating the probes and that is, why they are called nulling probes, as the probes are rotated then there are two different measurement (( )) at which pressure is measured, and then those pressures are equalized to a certain angle of rotation that also gives us an indication of the angel f or the flow at the exit.

So, nulling probes are usually used at the exit for measurement of angles, as well as some of these parameters like velocity, pressure and so on; so, let us now look at what are the different performance parameters, which are used in cascade analysis. I mentioned the measure basically velocity, then pressure that is both stagnation and static pressures of course, the flow angles, and from these measured parameters, what more can we do? what can we how can we post process these data that we have achieved from cascade testing, to get some information about the performance of these blades.

So, there are two basic performance parameters that can be calculated or measured from these test; one of them is known as the total pressure loss across the cascade, and the other is with reference to the static pressure coefficient on the blade surface.

So, cascades are basically stationary blades and so, there is no energy imparted on the flow and unlike a rotor, where there is an energy added to the flow and therefore, there is a total pressure rise in the rotor; whereas, in a stator, as you know, there is no energy addition, and because the frictional effects, there is actually a total pressure loss. So that is, what happens in a cascade as well that, there is a certain total pressure loss, which occurs as the flow passes through a cascade; and this total pressure loss is highly sensitive to the inflow angle that is the incidence angle that is, as you change the incidence angle, the rotor pressure loss also changes drastically.

And so, it is possible for us to from the cascade testing tell, what is the band of incidence angles, at which the total pressure losses are minimum or what are the angles incidence angle, at which total pressure losses increases substantially; and that will help us in keeping this in mind, when we take a detail analysis of the or design of the blade based on our knowledge of the cascade testing of these blades.

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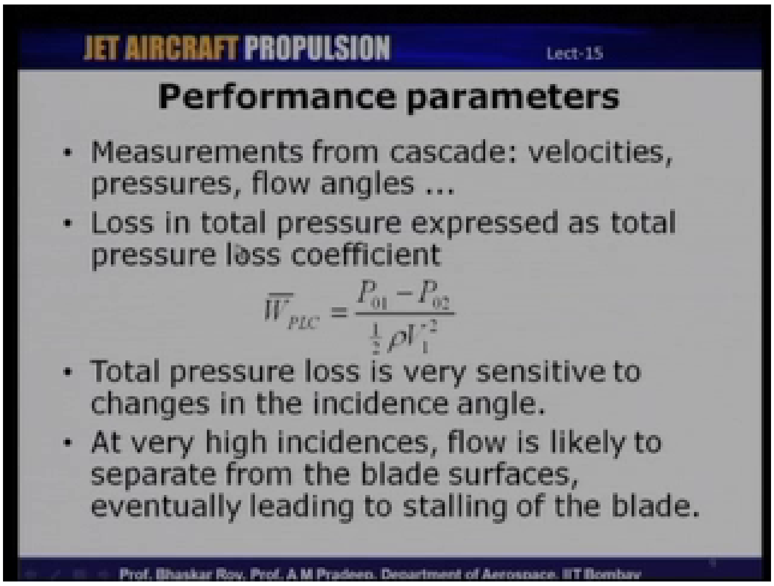

So, one of the parameters that we are going to define is based on the total pressure and the loss in total pressure across the cascade; so total pressure loss coefficient, which is denoted here, as W subscript PLC, which is pressure loss coefficient, is equal to P 0 1 which is the total pressure at the inlet of the cascade minus P 0 2 that is total pressure at the outlet of the cascade divided by half row v 1 square, where v 1 is the velocity at the inlet.

So, this is well the denominator is basically the dynamic pressure at the inlet; P 0 1 is inlet stagnation pressure, P 0 2 is exit stagnation pressure; so as you change the incidence angle, the inlet parameters are likely to remain unchanged that is the inlet total pressure, and the dynamic head remain unchanged, it is the exit stagnation pressure, which will keep changing.

So, as you keep increasing incidence, whether it is positive incidence or negative incidence, beyond the certain angle, the flow is likely to separate from the surface; and as it separates, it will eventually lead to stalling of the blades; you might have learned that, an air foil as you keep increasing the angle of attack of an air foil, beyond the certain angle, which is known as the stall angle, the blade will separate the flow will separate from the blade surface, and there is a drop in lift of the of the air foil; something very similar to that what happens here as well, that as we change the incidence, beyond the certain angle of incidence, the flow would separate completely from the blade section surface of the blade, if it is a positive incidence and that could lead to stalling of the blade.

So from the cascade testing, we could we can basically tell, what is the range of incidence angle, for which the blades are safe to operate, beyond which if we exceed the incidence beyond these angles, there is a likelihood that, the flow will separate from the blade surface. So, that is one of the aspects that is, we can measure total pressure loss across the cascade, and we can measure it as a function of incidence angle and so that, we know the sensitivity of these blades to the in a incoming angle that is the incidence angle.

The second parameter that we are going to define is related to the blade itself that is, what is the pressure rise on the blade surface or loss of pressure in terms of static pressure on the blade surface; so we are going to define this static pressure on the blade surface with, what is known as the static pressure coefficient or as usually denoted as Cp; so, Cp is basically the static pressure coefficient, which is defined as p local which is the static pressure local minus p reference pressure that is p reference divided by half (( )) v 1 square.

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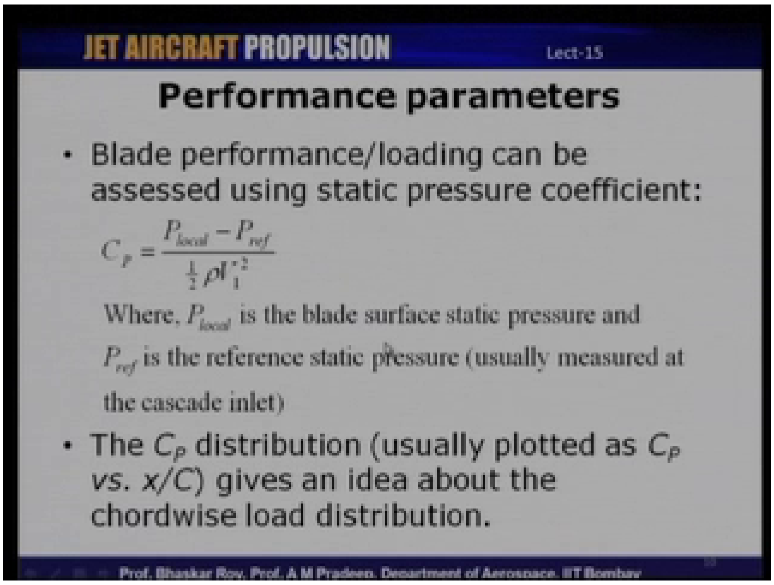

So here, P local is the blade surface static pressure at a particular point, which could be on the chord at any point on the chord of the air foil; and reference pressure is the reference static pressure, which is usually measured at the inlet of the cascade inlet in a similar fashion, as we measured P 0 1 in as defined in the previous definition.

So, Cp is measured on the blade surface and the Cp distribution, which is usually plotted as Cp verses X by C that is, the possession chord wise possession on the blade surface it basically gives us an idea about the load distribution that is, how the blades are loaded in terms of the pressure ratio. So, we can get some idea about the blade loading from the Cp distribution, as it is plotted Cp verses X by C; so, blade loading is one of the parameters we can infer from the Cp distribution of these blades.

So, we have defined two parameters, one is total pressure loss coefficient, which is basically the loss in total pressure across this cascade, the other is the static pressure rise coefficient; now, total pressure loss coefficient is measured at the trailing edge of the blade that is at the exit of the cascade, we move a probe, and as we as we traverse or move the probe, we measure total pressure at each point, compared that with the inlet total pressure, normalize that with the dynamic head inlet.

And so at the trailing edge, as we as the probe approaches the trailing edge, we would see a significant increase in the total pressure loss; this is basically because of the viscous effects as the flow passes on the blade surface, there is a viscous effect on near the blade surface at basically the boundary layer fluid, and that can lead to total pressure loss, very close to the trailing edge of the blade. So very close to the trailing edge of the blade, it is likely that, you see a certain a sudden increase in the total pressure loss coefficient; and away from the blade that is made passage between two blades that is, where the total pressure loss is likely to be the minimum.

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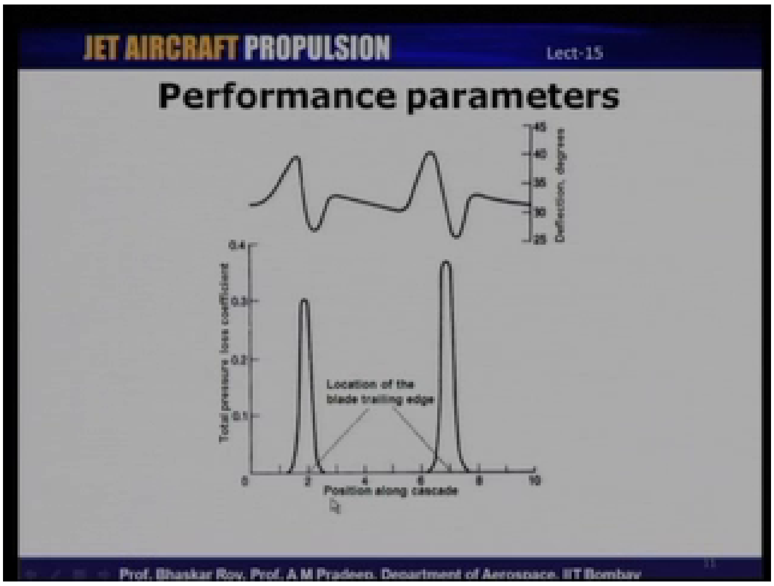

So, let me just show you one typical plot of, how the total pressure loss coefficient can change, as we change the location of the probe; so, as we move the probe, let us say from position 0 all the way up to 10, we it if we see such peaks very close to the blades trailing edge basically this or these corres these peaks are to see here, correspond to the trailing edge location of the blade trailing edge, and that is where you have the maximum total pressure loss due to viscous effects and the wake of the blade, wherein basically we have lot of total pressure loss.

And it is at these locations, as we can see, there is also a significant change in the deflection at the trailing edge that is, where which means that, the flow is exceeding the blade trailing edge at a slightly different angle than the blade angle at the trailing edge itself. So, as we move our traverse the probe along the trailing edge, it is possible that, we see such peaks in the total pressure loss coefficient, which basically a correspond to the location of the blade trailing edge.

So, as we change as the change the incidence angle, the magnitude of these losses across the blades also will change that is, as you keep increasing the incidence angle either to positive or the negative side, then the losses actually increase; and basically, because as you keep increasing the incidence, the extent of the wake subst shed by each of these cascade blades will also increase that is, the viscous losses on the blade surface will increase, as we increase the incidence angle.

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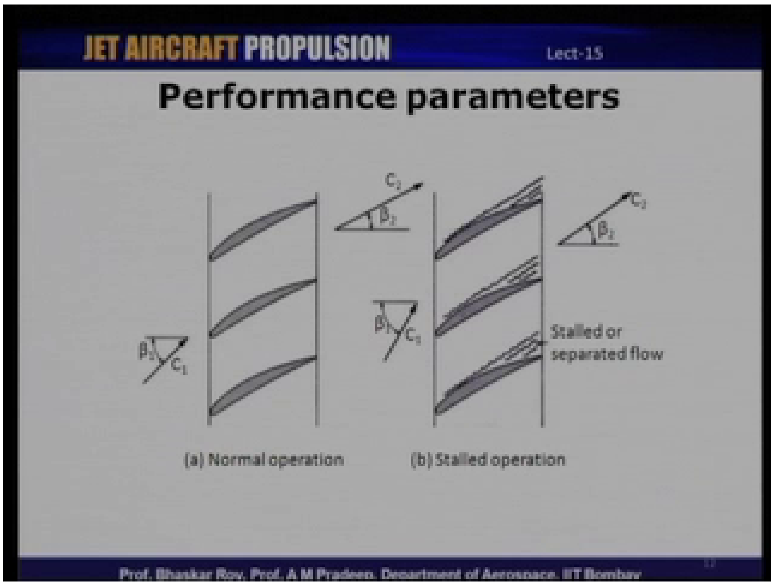

So, what basically will happen is that, if you were to look at a normal and a stalled operation of the blade as I mentioned, as incidence exceeds certain angles, the flow will separate from the blade surface leading to stalling of the cascade. So, let us take a look at two different cases; one is a normal operation of the blade and the other is a stalled operation; the incoming flow is that is coming in at a velocity c 1, the of an angle of either beta 1 or alpha 1, which is the same here; and the flow under normal operation comes in with zero incidence in this case, because the angles are the same, there is no angle between the velocity as well as the blade in that angle.

Flow enters the cascade and leaves the cascade at a an angle beta 2 at c 2, where as if you keep increasing the incidence, as the incidence is increased and the blade approaches that a very high angle, then the angle at which it is approaching is much higher than the blade in that angle itself, which means that, there is a possibility that the flow will separate from the suction surface of the blades.

So there is separated flow, as you can see here on all the blades and this can lead to stalling of the blade, which means that, the blade will no longer perform the way it should have been; the total pressure loss coefficient in this case would be substantially higher than what it was under normal operation. So as the incidence is increased beyond the certain range, then there is a risk of stalling of the blades and that is one of the aspects that, cascade testing should be able to tell us that what is the band of incidence, at which for which the blade operation will be safe.

So, if we were to look at incidence verses total pressure loss coefficient, each cascade blades a set of cascade blades will have a certain characteristics that is loss characteristic, which means that, if you were to plot total pressure loss coefficient on y axis and incidence angles, both negative and as well as positive then we would get a curve, which would tell us that, for these ranges of incidence angles, the total pressure loss is minimum. As you as we exceed the incidence angle, total pressure loss is substantially higher and those substantially higher total pressure loss values will give us an indication that, if the blades were to operate in that in those incidence angels, it is most likely that the blades were stalling.

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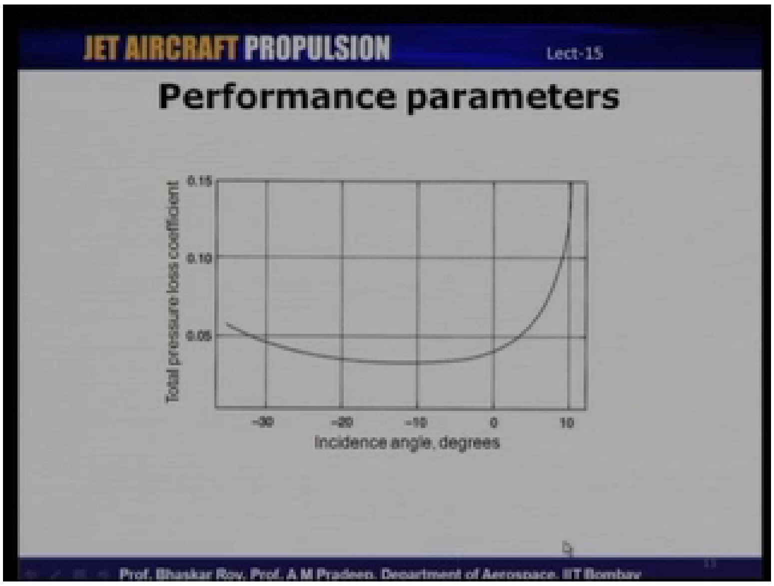

So let me show you one typical such characteristic, total pressure loss coefficient verses the incidence angle; this is for one particular cascade geometry, it will be different for different cascades. So what you shown here is, incidence angle both negative as well as positive incidence and total pressure loss on loss coefficient on the y axis; so you can see here that, there is a certain range, at least for this cascade, it seems to be a more comfortable with negative incidences, whereas on the positive incidence, we can see that the total pressure losses are substantially higher.

So if this cascade was to operate between, let us say minus fifteen all the way up to 0 degrees, the total pressure loss is more or less the same; whereas, if we an if it were to be operating at an incidence of 10 degrees, total pressure loss is substantially higher than, what it was at minus 10 degrees.

So from this is some information, this is one of the forms of information of those, which you can obtain from the cascade testing at different incidence angles, wherein we can get some idea about the loss coefficient as the incidence angles are changed; of course, incidence angles of minus 20 degree or minus 10 for that, matter is a very high incidence; normally, incidence angles are kept close to 0, it is very kept very low, because performance of the blade is very sensitive to these incidence angles. So, total pressure loss from the cascade testing is one of the parameters that, we get one of the information that, we can get from testing of these blades in a cascade.

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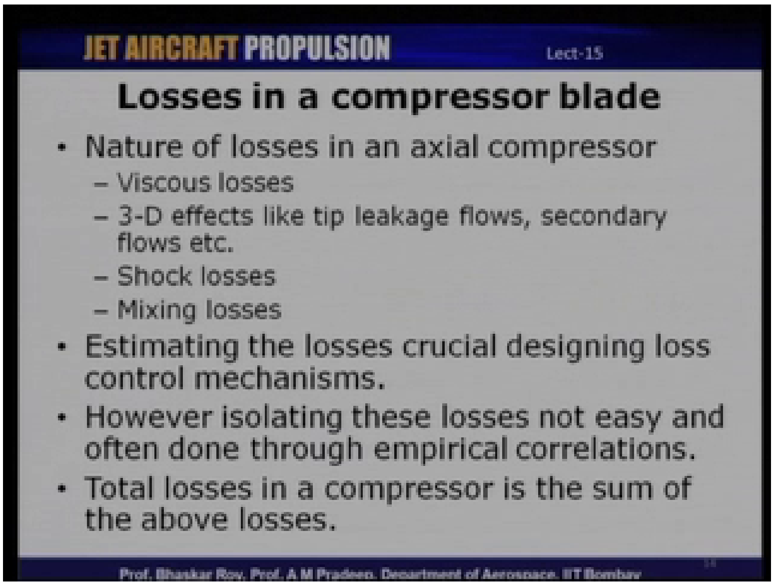

Now, let us now look at, what are the different forms of losses in a compressor blade; there are different types of losses, which we can identify thou that, those are associated with compressor blades, not just cascade it, its true for any compressor blade as such. One of the forms of losses are known as viscous losses, we will discuss that also little later; viscous losses the second form of loss is 3D effects like tip leakage flows or secondary flows, these are not necessarily viscous flow, viscous related effects, but these are also present in potential flows.

The third type of losses could be shock losses, which are true for transonic compressors or those compressors operating very close to of the mach one, at least the relative mach number and then the last form type of losses are mixing losses. So it is necessary that a designer if able to have some indication or some estimation of these losses basically, because it is required as a part of the design, we need to know what kind of losses are present in axial compressors and how is it that we can estimate these losses.

But of course, these losses do not exist in isolation; there is a combination of all these losses present in a compressor; so it is very difficult to distinguish and isolate individual components of these losses; and total losses in a compressor is basically the sum total of these individual components of losses.

So, viscous losses are of different types; now viscous losses as you can guess is due to the viscous effects and the presence of boundary layer and so on; so the diff[-erent] there are different forms of viscous losses; one such form of viscous loss is the profile loss; profile loss is basically because of the shape, the basic geometry of the air foil itself and so that can lead to certain amount of skin friction losses that is known as the profile loss.

The other form of viscous loss is known as annulus loss; annulus loss is basically because of the growth of boundary layer, at both the ends that is at the hub end as well as the casing end; and as we move from the inlet of the axial compressor, all the way for a multi stage compressor at the exit, the boundary layer thickness keeps growing and so obviously there is an increase in annulus loss from inlet to the exit.

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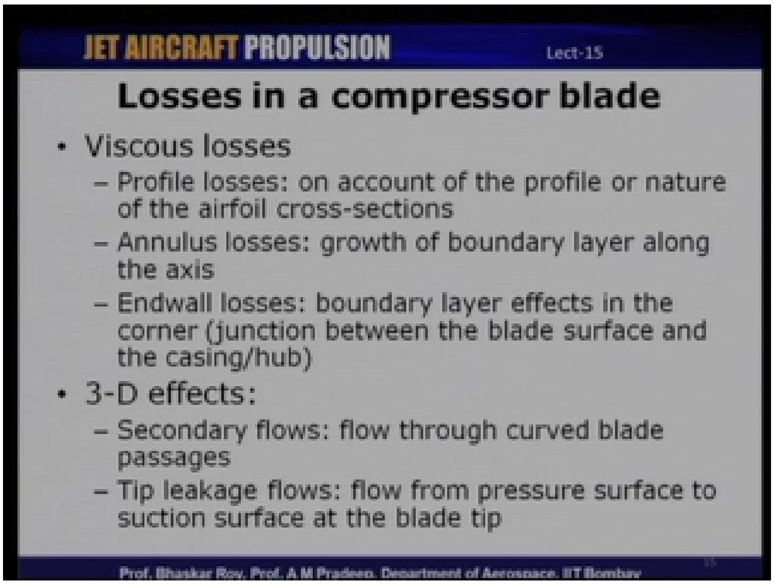

And the third type of viscous loss are known as end wall losses; end wall losses are due to the boundary layer effects in the corner that is junction between the blade surface and the casing or the hub; and so, because of these corners, there are corner related losses we basically referred to early end wall losses.

So, there these are three different forms of viscous losses and so, in an in an actual compressor you one would have a combination of all the three different forms of the viscous losses present; the other form of loss is the 3D effects; 3D effects include the secondary flows that is basically, as the flow passes through a curved passage, there are flow components, which are introduced, which are in addition to the normal flow component itself ,these are known as the secondary flows, and losses associated with these are known as secondary flow losses.

There could be then, tip leakage flows that is, this is true for a rotor blade tip leakage flows are not necessarily present in its stators, where the blades are fixed at both the ends; in a rotor, where the blade is fixed only at the hub and that the tip, it is free the that is the flow, which escapes from the pressure surface to the suction surface that is known as the tip leakage flow.

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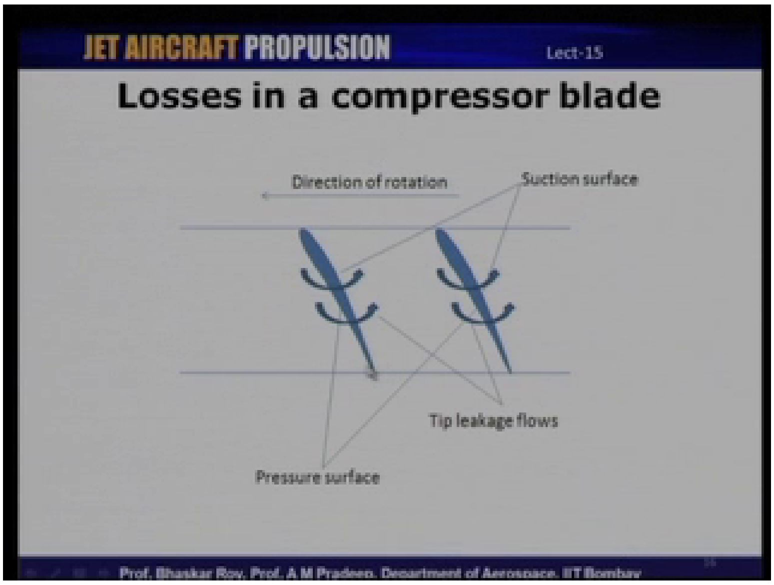

So tip leakage flow basically involves flow from the pressure surface; this is the pressure surface of the blade and this is the suction surface of the blade; at the tip of the blade, because its open, it is not fixed to the casing flow from the pressure surface leaks or moves towards the suction surface; and then, because of the rotation and the incoming flow, it escapes in the form of a vortex and that is known as a tip leakage vortex

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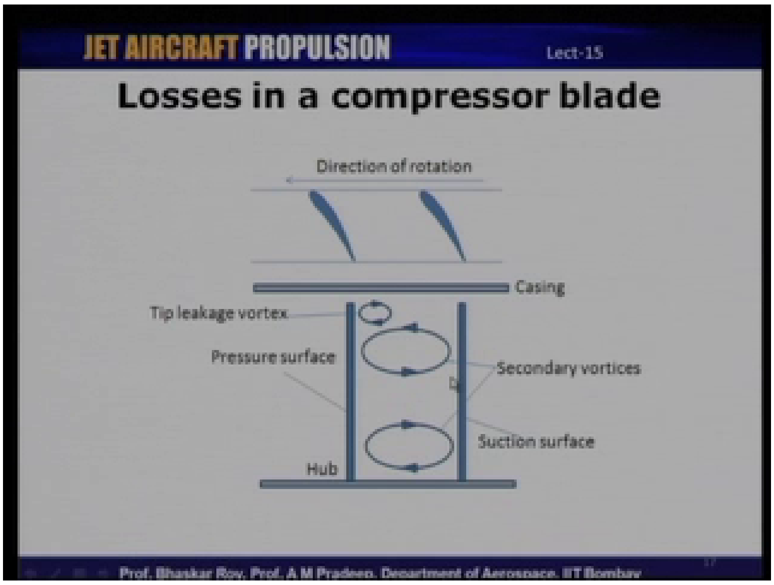

So if we were to look at this in a simple schematic form in a in a rotor blade, let us say this is the pressure surface of this particular blade and this is the suction surface of this blade; tip leakage vortex is flow from the pressure surface to the suction surface, and that manifests itself in the form of a vortex, and its known as the tip leakage vortex.

In addition to that, because the flow is passing through a curved passage, they would also be in the presence of these secondary vortices or secondary flows as they are also known as; and so there is a loss of total pressure in all these that is, because of the tip leakage vortex as well as the secondary vortices, loss of total pressure associated with all these.

So these are basically because of the three dimensional effects; suppose the blade was to be fixed at this end, and there is no boundary layer around this the surfaces that becomes the two-dimensional flow and the presence of tip leakage vortex is absent in such a flow; so tip leakage vortex is purely at three dimensional effect.

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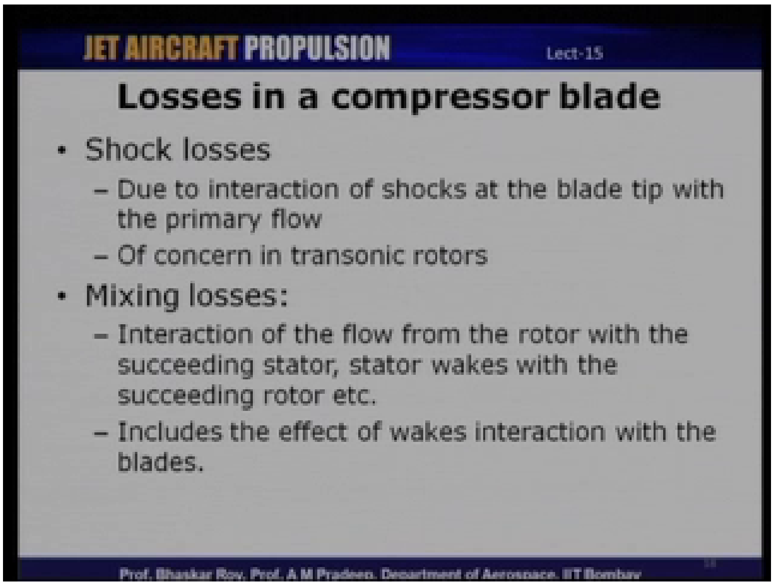

And the other forms of losses are shock losses; shock losses are basically because of interaction of shocks at the blade tip with the primary flow; and its by basically of concerned in transonic rotors that is, modern day fans and compressors tent to have relative mach numbers in supersonic regime and so these are basically known as transonic rotors and there is loss associated with the interaction of shock, and the primary flow and the boundary layer.

And the last form of losses are known as the mixing losses; basically because of interaction of the flow from the rotor to the stator or the stator wakes with the succeeding rotor and so and so it is basically the effect of or interaction of the wakes, which are as a result of the rotor or the stator interacting with the subsequent stage. So, mixing losses basically pertain to interaction of these wakes with the subsequent stages; so all these losses put together or to some total of all these losses are equal to the total loss that are incurred in a compressor stage.

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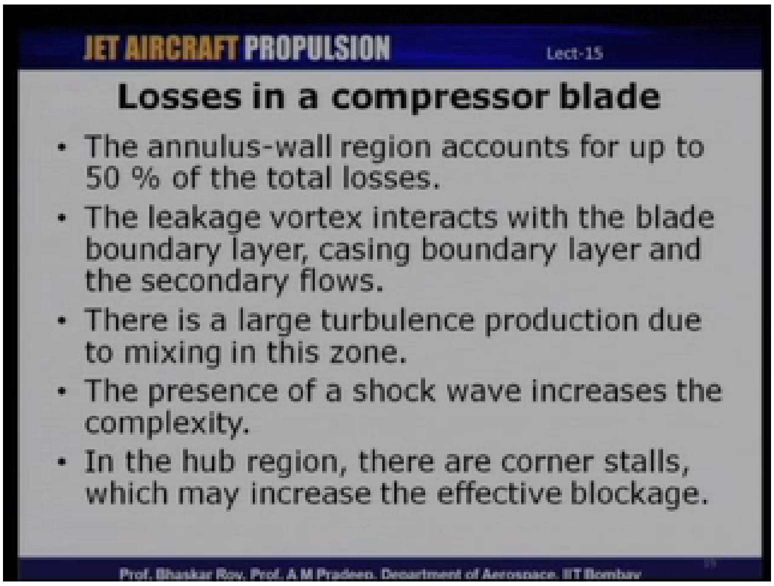

So in the annulus wall regime basically, it can actually account for about that is basically the viscous losses can account for almost 50 percent of the total loss; leakage vortex can interact with the blade boundary layer, casing boundary layer and secondary flows; and as a result of this there is a there is a large turbulence increase in the mixing zone, because of the interaction of the wakes with the subsequent stages.

And if, there is a shock wave presentence in the case of transonic rotors, there is an additional complexity, which is which is introduced; and in the case of a hub, if you are looking at the hub regime, there are also a presence of corner stalls, because of boundary layer growth on the blade surface and the hub surface itself. So as you can see here, there is a very complex complicated interaction between these different loss generating mechanisms; and interaction of all disc makes it very difficult for one to segregate these different loss components, and estimate these loss components individually. In literature, you will find lot of empirical correlations, for estimating these loss components; and of course, as they are empirical in nature, they are not very accurate for all different for a range or variety of a compressor geometries, and there is a geometry dependence on in most of these empirical correlations.

So, what we have discussed today, let me just recap our discussion in today's lecture; we were discussing about cascade; we started our discussion with cascade and defining what is a cascade; we had a look at, what is a typical cascade wind tunnel and what are the other forms of cascade tunnels, which are prevalent; and we also discussed about nomenclature, which is associated with a cascade; and then we also discussed about the parameters that we measure from a cascade testing and the information that can be achieved as a result of cascade testing. Then towards the end of this today's lecture we also discussed about the losses that, how do we classified broadly classify losses in an axial compressor, and what are the sources of these different losses.

So, these are some of the topics that we discussed in today's lecture, and we will continue our discussion on axial compressors in the next lecture as well; we will have some discussion in next lecture on, what is known as a free vortex theory; we will have some preliminary discussion on free vortex theory.

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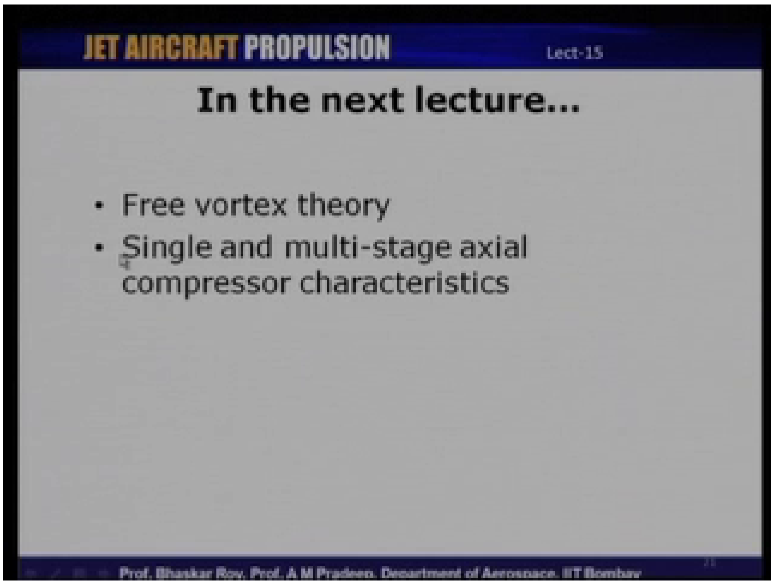

We will then discuss in detail about the characteristics of axial compressor; we will begin discussion with single stage axial compressor characteristics, followed by a detailed discussion of multi stage axial compressor characteristics. So, we will take up these topics for discussion during our next lecture that would be lecture number sixteen.