Turbomachinery Aerodynamics

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Lecture No. # 06

3D Flows in Blade Passages, Secondary Flows, Tip Leakage Flow, Scrubbing

We are talking about various aspects of a flow through turbomachineries and we are dealing with aerodynamics of the turbomachinery; you have gone through a couple of lectures in which you have been introduced to the various aspects of flows which are considered to begin within a two-dimensional manner. And that two-dimensional understanding is indeed very important; you need to keep that in mind. As we go forward, we will be looking into those two-dimensional understandings and two-dimensional theories more and more, going into various aspects of turbomachinery aerodynamics, it is design an analysis. However, we need to understand that the flow through turbo machineries is indeed very three-dimensional in nature. This three-dimensional understanding needs to be followed up with a certain amount of analysis, which we shall do later on in terms of computational fluid dynamics.

But today, I will introduce to you the three-dimensional nature of the flow through turbo machineries; and especially, right now, we are looking into axial flow compressor. In axial flow compressor, the flow tends to become three-dimensional as soon as the flow enters the rotating rotors. The rotational nature of the blades introduces three-dimensionality; because, the flow comes in actually, as the name axial compressor suggests. But as soon as it enters the rotor, it acquires this rotational component of the flow in passing through the rotor.

So, that is the first introduction to three-dimensionality. There are various other reasons; as we go along, we will see that flow also tends to acquire certain amount of radial component of the flow. Now, these three-dimensional components of the flow are inherent in any axial flow compressor, more so in the modern axial flow compressors as used in aircraft engines, where if the compression ratio of a single axial flow rotor is much higher today, than it was, let us say 30 or 40 years back, and as a result of which the high pressure ratio introduces more three-dimensionality into the flow through these rotor blades.

Today, we shall look at how this three-dimensionality, actually is acquired; and then, what is the repercussion of this three-dimensionality of the flow through axial flow compressor. So, today's lecture is on three-dimensional flow through the blade passages in axial flow compressor.

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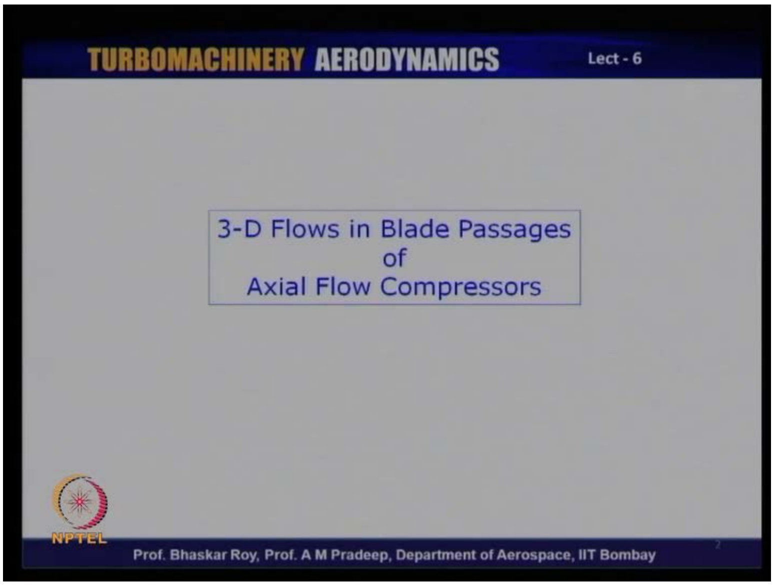

As I mentioned, the flow acquired three-dimensionality to begin with; when it enters the blade passage, the rotating blades is the first thing that introduces this three-dimensionality. However, we need to understand that, as the pressure ratio across the blades or across one rotor is increased with increasing pressure ratio of the entire multistage compression system, the three-dimensionality that it acquires is indeed more and more. So, let us see, to begin with how this two-dimensionality of the blade shape also comes into the picture.

The flow acquires rotational component, but as we will see, that the blade also acquires a three-dimensional blade shape, a very complicated blade shape or twisted blade shape and let us begin to see how it acquires this three-dimensional blade shape.

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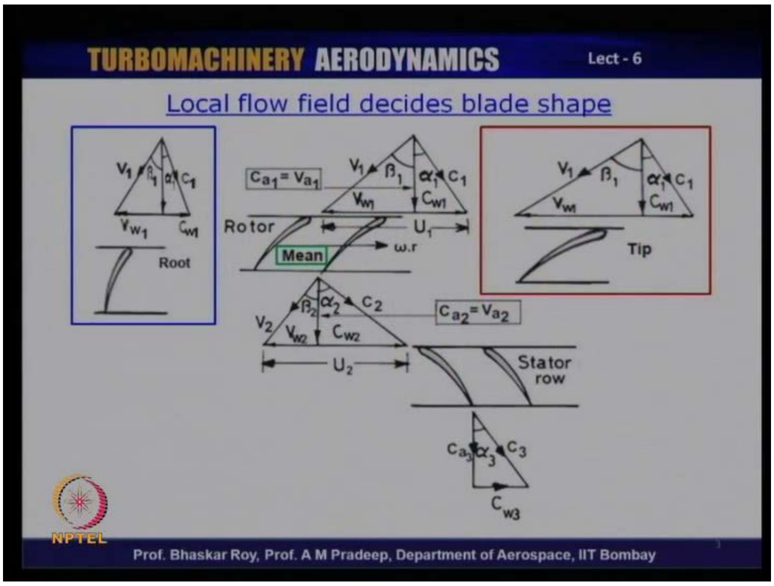

If you look at this picture, it is essentially take off on the two-dimensional understanding that you have just gone through. The flow entering a typical blade, actually if you take two-dimensionally has encountered, let us say, these velocity vectors, as it enters the blades; and, these velocity vectors let us, say, if you take at the mean of the blade, it acquires the velocity relative velocity V 1, which means that your rotor would have to be now oriented towards this relative velocity V 1; so, that the flow enters the rotors blades in the relative frame of reference and interacts with this rotor and acquires energy transferred from the rotor to the stator. The rotor is rotating in this direction as it is shown by omega r,

Originally, if you see the flow was coming along this direction which is C 1, at an angle of alpha 1, it acquires an angle beta 1 by virtue of this vector diagram, and this V 1 at an angle beta 1 is the velocity which is going into the rotor in the relative frame, in the rotational frame. And then of course, as we have done before, it comes out of the rotor, initially in the relative frame, in the direction V 2, and then it acquires absolute flow direction C 2, with which it goes into the stator and gets future defused to complete the compression process.

Now, what happens is, the rotational component u, is a product of omega n r. Now, r is a variable along the length of the blade from root to tip; now, at the root, you see, the value of u is going to be much less than at the mean. And as a result of which the velocity triangle that you see now is quite different from what you would see at mean, and as a result of which it acquires the velocity V 1, at an angle beta 1, which are completely different from what it had at the mean section of the blade. And, as a result, it is going in with a different velocity V 1 at different angle beta 1, into the root section of the blade; and this velocity V 1 is much less at this angle beta 1 with reference to the actual direction, is much less.

And correspondingly, the rotational component of V 1, that is, tangential component, V w 1 is also much less, even if, let us say, C 1 remains of same order. As a result, the root section of the blade now needs to be oriented towards this direction, and hence the orientation of this root section is quite different from the orientation of the mean section.

So, the root section as to be at a different angle and the mean section would have to be at a different angle with a consonance with the flow angle with which they are coming in, that is related flow angle, with which they are coming in. Now, if you move to the tip of the blade, where again the omega r, r is of a much higher order; omega remains constant from root to tip.

So, the U on here is of a much higher order; and as a result of which, again if C 1 remains same, alpha 1 remains, let us say same C w 1 remains same, V w 1 is now quite different and beta 1 is quite different, V 1 is quite different. Now, the flow is at a much higher velocity and it is at a much higher flow angle with reference to the actual direction.

And hence of the blade section here, the aerofoil section here, would have to be oriented towards this direction, which is something like this, and hence the tip section is now needs to be oriented at a completely different direction compared to the mean and the root section. Now, this introduces the three-dimensionality of the blade shape. And this three-dimensionality then acquires a hurly twisted blade shapes depending on the design, depending on the design choices of the designer and depends, of course, as I mentioned, on the pressure ratio that is to be imported to the fluid, through this particular blade row; all of it together creates the blade shape.

So, creating the blade shape is a very complicated procedure. We will be going into creation and design aspects of the blade, a little later in this lecture series, but at this moment, I hope you have understood that it is necessary that the blade sections acquire different orientation at the root, at the mean and at the tip. So, from tip to a root, the blade acquires a twist and this twist is inherent to the flow of the, nature of the flow that is going into the compressor rotor. And that is what I have just tried to explain to you here, through these simple diagrams which are essentially carry over from your two-dimensional understanding of the flow through the compressor stage.

So, you see, the flow not only acquires through three-dimensionality because of the rotation of the blade it acquires three-dimensionality and a twist of the blade, simply because, also of the rotation of the blade, and how much twist or how much three-dimensionality depends wide substantially on the kind of design and kind of flow that you would like to create within the rotor blade. So, the three-dimensionality of the blade shape and three-dimensionality of the rotor flow are inherent to modern axial flow compressor. And this is something which every compressor designer has to take into account, right from the beginning, from its design and then through its analysis and finally, the performance prediction.

So, the two-dimensionality that you have done in the earlier few lectures, does carry over, does continue and we would need to keep that in mind going in to the three-dimensional understanding of the flow through the compressor rotor blades. Let us quickly understand, what kind of blade shape that we are talking about.

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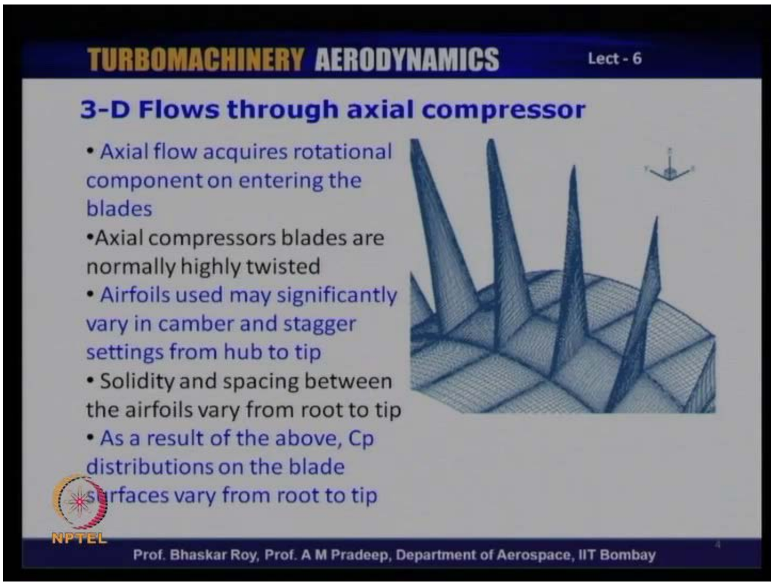

If you looking into blade shape here, you can see that the blades are in the twisted; and as I mentioned, the amount of twist does depend on the particular compressor and it varies from one compressor to another, quite a lot. So, it acquires rotational component on entering the blades, it may have been absolutely uniform and actual in nature, before entering the blades; but once it enters the blade, it automatically acquires certain rotational component. The modern axial compressor blades are indeed highly twisted and I have just explained in the last slide, how this twist is indeed important to the blade shapes.

These blade shapes, as you know, are made up of aerofoil sections. These airfoils may significantly vary in camber and in there stagger setting; that is the angle at which each aerofoil is set from hub to tip, and that is also been explain in the last slide, how the stagger needs to be vary from a root to the tip of the blade. And also, we have seen; let us go back just for a minute; we have seen that the flow that comes into the root section is most likely to have a velocity much lower than at the mean, and at the tip, it is even higher.

So, the flow velocity at the tip is highest, at mean, its median at the root, it is lowest; and as a result of this change of velocity, quite substantially in the modern axial flow compressors, requires that you may like to use different kind of aerofoil sections. For example, near the root, your velocity that you are encountering is low velocity; you may like to use aerofoils at a good for, comparatively low velocity fields. Whereas, at the mean, you are encountering median velocity, so, may, you may like to use another kind of aerofoil, which are good for that kind of velocity field; whereas at the tip, you are encountering very high velocity and you may like to use thin aerofoils which are good for high velocity fields.

So, you may go from low velocity, which could be low subsonic or median subsonic to high subsonic to transonic or even supersonic flow at the tip. And as a result, you may like to use a low subsonic aerofoils, here the root; high subsonic aerofoils at the mean; and probably, high subsonic or transonic supersonic aerofoils at the tip.

So, that is how the camber of the blades would change significantly from the root to the tip of the blade. Now, as you can see, the blades are more or less created in a manner, they are built up, sort of tangentially. So, the root to the tip, all the aerofoils, you may have designed something like 8 or 10 or 15 aerofoils and those are to be stacked. Now, stacking is often, almost a nearly radial; and as you stack them up, as you can see here in this diagram, as you stack up the aerofoils from root to tip, the spacing between 2 aerofoils at the root and the spacing between 2 aerofoils at the tip, would automatically be different; spacing at the tip would automatically be much more than at the tip; and of course, at the mean, it will be median.

So, the solidity of the blade which you, as you have done before, is defined as cord bi-spacing of a particular blade, would vary from root to the tip of the blade, quit substantially in most modern axial flow compressors. Now, since you are using different aerofoils of the different camber, different stagger, different velocity field, different solidity and shaping, it follows, that the c p distribution of the coefficient of pressure distribution over each of these aerofoils sections, from root to the tip of the blade, would also automatically vary substantially. Now, this variation of c p from root to tip, as I mentioned, happens automatically the moment the flow enters the blade, and the blade as the three-dimensional twisted blade shape. So, this c p distribution is something we should like to look at in a minute or so.

Indeed, it produces a flow field, because C P is nothing but essential denotation of the pressure on the surface of the blade, static pressure on the surface of the blade, which being that the static pressure field on the surface of the blade is varying substantially. This variation from root to tip and from leading edge to trailing edge would create a static pressure field all over the blade surface, two surfaces, and this would indeed is the genesis of the beginning of creation of highly three-dimensional flow field, which is what we are studying in today's lecture. So, this c p distribution is something which is then inherent to the blade shape and the blade flow.

Let us take a look at what kind of blades we normally arrive at, as soon as we have created a blade.

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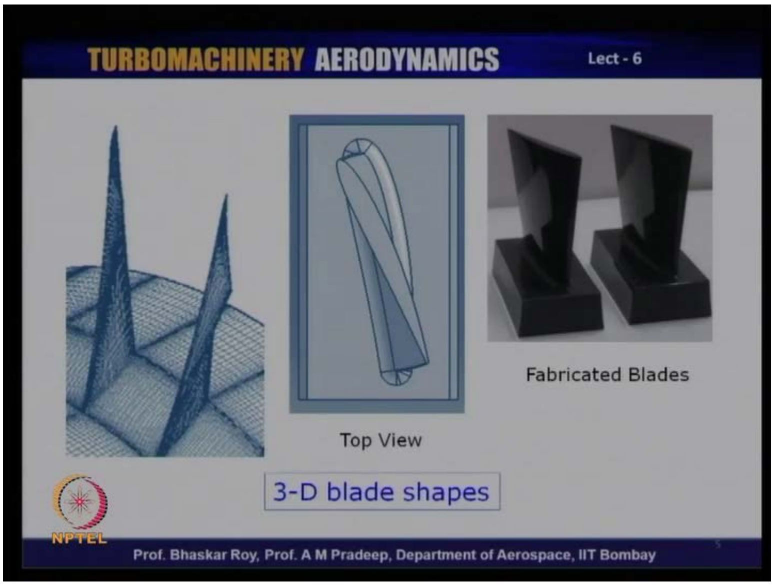

If you look at the blade here now, as we saw in the earlier diagram, it acquires a twisted blade shape like this; this is a graph of, picture graph of a geometric modeling in computer of and it is a top view of a blade. As you can see here, what we can see here is the top aerofoil section and its twisted blade like this.

So, the bottom aerofoil section is over here; this is the suction surface and this is the pressure surface of the root aerofoil section, whereas this is the tip aerofoil section. This is a picture of fabricated, twisted blade; and as you can see, the twist is very visible and as a result of which, from the tip to the root of the blade, a very clear twist is mandated by design of every blade. And, as I mentioned, these 3D blades shapes are indeed acquired in the process of the design of the blades; and then of course, the blades about need to be analyzed very accurately to understand what is happening in the three-dimensional nature of the flow inside these blades and the blade passages.

So, let us take a look at what happens to the aerodynamics of the flow when it enters this kind of blades and the blade passages. As I mentioned, the flow acquires a certain amount of C p distribution from root to tip. Now, this C p distribution is actually denotes the pressure distribution, static pressure distribution on the blade surface. Let us take a look at what are we talking about.

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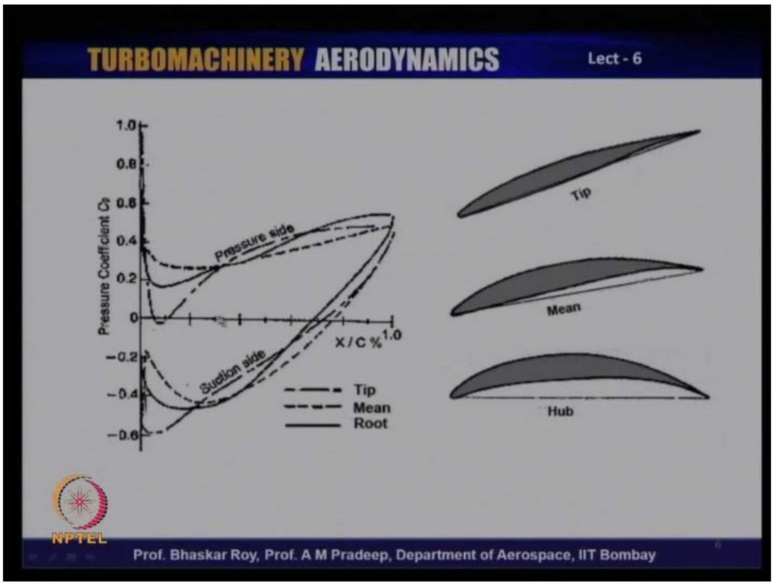

If you look at this picture, I have tried to show you here, this is, let us say, a tip section of the blade, this is the mean section of the blade and this is hub; and tip, as I mentioned, could be at a different angle, mean is an median angle and hub is quite often almost nearly axial or pretty close to axial. If you take the C p distribution, this blade is, as you can see here, the hub blade has, the root blade has very high camber, the mean blade has a medium camber and the tip blade has very low camber.

So, this is what we are talking about. And, it stand, to reason from fundamental aerodynamics of the aerofoils, that they would have different C p over these blade sections. Now, that what is shown here, in the C p diagram over here. This is the pressure side, which is this side; this is what we call a pressure side, and more curved side is what we normally call the suction side.

So, the tip section here is shown by the chain line which as a sharp development of C p near the leading edge and then a long diffusion over it surface. A mean section is shown by the dotted line, which is also quite often to begin with, taken as a representative of the entire blade section. And the root section is the solid line, which is more curved; as you can see, its symptomatic of the highly cambered blades shape that is given to the root and then it as a diffusion going into the trailing edge. The pressure surface also shows a similar sharp, nature, near the leading edge, at the tip, and much less near the hub and the root sections.

So, the nature of the aerofoil section that is used at the tip and the mean and the hub and that they are at different angles, create this C p distribution over the individual blade sections. If you are, therefore, creating let us say, 10 or 15 blade sections from root to tip in the process of your design, which is what the modern designers do; they indeed create 10 or 15 or more blade sections depending on how big the blade is, the modern axial flow fan, which is, you know, that big would have indeed 30, 40 blade section and aerofoils sections created. So, all of them would have different C p diagram of its own.

So, each of the aero-foils would have its own C p diagram as shown here; and all those would have to stacked up aero-dynamically and geometrically, to create one single rotor blade. So, this is how the aerodynamics of the blade begins, that you have fundamentally a variable pressure distribution on the blade surface from root of the root of the blade to the tip of the blade.

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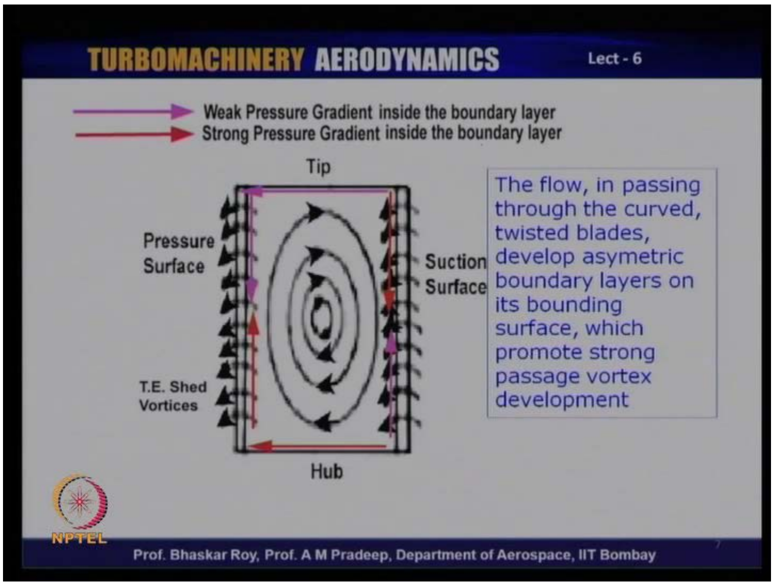

Let us move forward and see what happens if you do have this kind of a variable pressure distribution from the root to the tip. Near the hub, as you can see, you have a solid surface. Typically, a blade would have four solid surfaces bounded in the passage between two blades; this is one blade, this is one blade. On one side you have a tip, on another side you have the hub and on two sides you have two blades. Now, one of the lade surface on this side is a pressure surface, on the side you have the suction surface and as you have seen, the two surfaces are dissimilar in curvature.

So, we have four surfaces which are essentially dissimilar in nature and the passage between the blades is then bounded by four surfaces which are dissimilar in nature. This dissimilarity, of course, creates the variable pressure distribution from hub to tip, from this surface to that surface. So, pressure is continually varying form hub to tip, along the blade surface or each of the blade surfaces; it is also varying from pressure surfaces to suction surface, along the hub and also along the tip.

So, if you look at this diagram now, you would that pressure varies along this surface, it varies along the surface, is varying at the tip from here to here, is varying from hub from here to here. Now, to begin with, at the hub, you see, it is pressure surface; pressure over here would invariably be higher than the pressure over here; and also at the tip, the pressure would be higher over here than at over here, because of the suction surface. But, the pressure differential over here and the pressure differential over here are different; this is at the hub, this is at the tip.

So, the difference in the pressure over here is different from the differential pressure at the hub, between the two surfaces. Now, on the similarly, the differential pressure from hub to tip can also vary and this variation is shown over here. On the pressure surface, you have a certain nature of variation; on the suction surface, you have certain nature of variation. It is entirely possible depending on the blade design, it is entirely possible that the pressure would indeed show a rise from here to here, from tip to the medium and also from hub to the mean. Again it may show a variation, a weak variation from hub to the mean on the pressure surface and some out stronger variation from tip to the mean on the pressure surface. So, how it could vary would indeed depend on the design and depend on the blade shape. So, the pink line shows here the weak pressure gradient and the red line is the strong pressure gradient.

So, flow, in summation, in passing through the curved twisted blades, develop a strong asymmetric boundary layer on its bounding surfaces. There are four surfaces which are dissimilar to each other and which promote this strong passage vortex creation. What happens is, these boundary layers then, are created because of the pressure gradient, along the solid surfaces; and on the solid surfaces as you well know, you have boundary layers. Within the boundary layers, there is fluid movement from high pressure to low pressure, from high pressure to low pressure as shown by the red and the pink lines; and these movement of fluids within the boundary layer, initiates a motion of fluid, as the flow passes through the blades, and it acquires a passage vortex shape like this. And, certain passage vortex is then created as the flow pass through the blades; even if the flow entering the blades is absolutely uniforms and actual in nature. In passing through the blades, it acquires this, a passage vortex, because of the static pressure distribution all over its blade surface, as shown in this diagram. Now, it is entirely possible, as I mentioned, that the nature of development of this passage vortex depends on the blade design and the blade shape. So, if you have slightly different kind of a blade design, you may have a different kind of passage vortex development.

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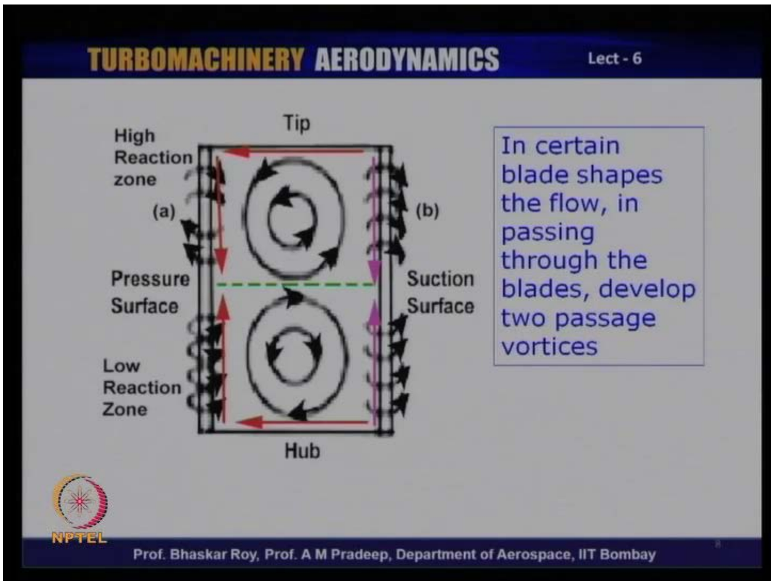

Now let us see, what happens if you have slightly different kind of blade design. The blade shape here promotes two passage vortices; one in this way and other in the counter rotating way. So, it is entirely possible that you get two passages vortices coming out, counter rotating to each other. So, this rotational nature is now counted to each other. So, on the top half of the blade, you have a passage vortex; looking at it from the rear of the blade, you may see a passage vortex creation which is, let us say a counter clockwise, whereas, one at the bottom is essentially a clockwise passage vortex creation.

Now, this is due to the particular kind of design. We will be talking about the certain design theories a little later in this lecture series, but at this moment, I will just say that the nature of the pressure gradient that is created on the bounding surfaces, initiates this flow; and as a result, if you look at these arrows, it tells you that these arrows, these are the strong arrows which means this is the strong pressure gradients and this is a weak pressure gradient.

So, on this strong pressure gradient overpowers the weak pressure gradient and creates a passage vortex in this direction, which is counter clockwise. On the bottom half, the strong pressure gradient is this way, as shown by the red lines and the weak one is shown by the pink line. So, again, the strong pressure gradient overpowers the weak pressure gradient, it is strong enough to overpower, and as a result, it creates a clockwise as seen here, a passage vortex. So, two passage vortices may be created through the, as the flow passes through the blades and as a result of which, two passage vortices would be coming out of the blade at the trailing edge of the rotating blade.

So, what kind of passages vortex is created, is decided essentially by the blade shape, by its design original design and the nature of the flow through the blades. And hence, you need to analyze the blade shape in great detail, even after the design, to know what kind of the passage vortex are being created, what is a strength of this passages vortex; because, these passage vortices are not useful to the creation of the compassion, they are losses.

The energy that goes into creation of these passage vortices are essentially lost as far as the compressor process is concerned; and as a result, they are consider as secondary flow and they are consider as secondary flow loses. These losses are irretrievable, you cannot get them back. Hence, passage vortex creation is not something that you would like to have, but they are inevitable; you have learn to live with them and try to keep them to the minimum, because they are all loss making proposition. So, these passage vortices are inevitable, but you need to keep those passage vortices strings, as low as possible, by design and analysis, so that the losses in the process of creation of those passage vortex are indeed minimum.

Let us look through various aspects of passage vortices, putting the two figures together. As you can see here, on the left hand side, you have one strong passage vortex creation, which comes through the blades. In the second one, you have two passage vortices coming through the blades; it depends, as I mentioned, on the design of the compressor blades. You need to analyze and find out how much is the strength of this passage vortices and what is the amount of energy it is carrying away; because, as I mentioned, that energy is not available to the rotors for compression of the fluid. You may have to sometimes, redesign the blades after the analysis, to ensure that these secondary flow creations are low in strength, so that the losses that are incurred are also on the lower side.

Let us move forward and see what happens when you have a compression of the fluid. You see, flow through the compressor is essentially flowing in an adverse pressure gradient. We have talked about this before in the earlier lectures, the flow in compressor is always in a adverse pressure gradient. Now, if you at the flow track through the blade, through the rotor, through the stator, it is flowing in a adverse pressure gradient the entire flow. And, as a result, the bounding surfaces that we are talking about, is always encountering adverse pressure gradient flow, and hence it has a strong tendency towards development of boundary layer; on the blade surfaces, which of course, as you have learnt, tends to create flow separation on the blade surface. But here, we will talk about the other boundary layers; that is the one at the casing and at the hub.

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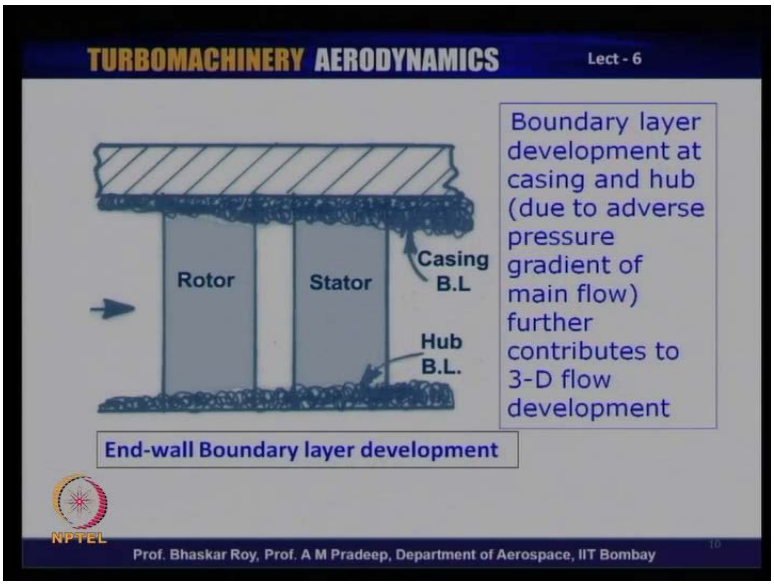

If you look at this picture now, it shows that there is a strong bound layer development as the flow enters the rotor; it may have entered with a little boundary layer from builder, say, from the previous stages; but as it goes through this particular stage, it develops far more thicker boundary layer; on the casing as well as on the hub. Now, this boundary layer development, essentially has two repercussions; one is, it contributes to the three-dimensional flow development. You see, the flow over here, near the casing, is deflected inwards, and the flow at the hub also is deflected inwards. So, the flow near the hub and at the casing, acquires a radial component by virtue of the deflection; we just studied in the previous slides, how it acquires tangential components. Now, we will see how it acquires radial components by virtue of the development of boundary layer at the casing and at the hub.

And, as a result of which, the flow is, as I mentioned, deflected inwards. There is another problem, and that is, these boundary layers, as you know, are low energy fluids. The growth of the boundary layer essentially creates certain kind of a lockage; that means, they have a tendency to block the main flow. The main flow is here, from here to here, from hub to the tip; it is entering the rotor going through the rotor, going through the stator and it is getting delivered at the back to, may be, another stage. Now, this main flow, now here, as you see, as it is coming out as a much lower area compared to what it came in with.

And as a result, the flow has got constricted and one can say that the boundary layers have created fresh blockage to the flow. This blockage is an important problem, because what happens is, the flow has a tendency to lose some of its mass flow. The mass flow through the blade may then get actually reduced; so, the blockage has a tendency to reduce the mass flow going through the blades. Now, this is an important issue, because, if we are talking about a gas turbine engine, an engine that creates thrust; as you know, the thrust of an engine is directly proportional to the mass flow.

Now, if virtue of the boundary layer on the bounding surfaces of the blades in axial compressors, there is a blockage of the flow, the flow through the compressors is partially blocked; that means, the mass flow is reduced, and hence the flow through the entire engine would be substantially, then reduced and hence your thrust would be reduced. So, blockage created by these involved boundary layers is indeed a threat to the final thrust that is created by the engine. So, this is an important problem that needs to be addressed; and, we shall see how we can try to take care of it. Blockage, again, is an inevitable, it is an inevitable creation of the three-dimensional and real flow through the blades bounding surfaces. There is nothing much you can do about creation of the boundary layer; by design and flow analysis, you can try to keep the blockage as low as possible. So, blockage is inevitable, but you can try to keep it as low as possible by design and analysis.

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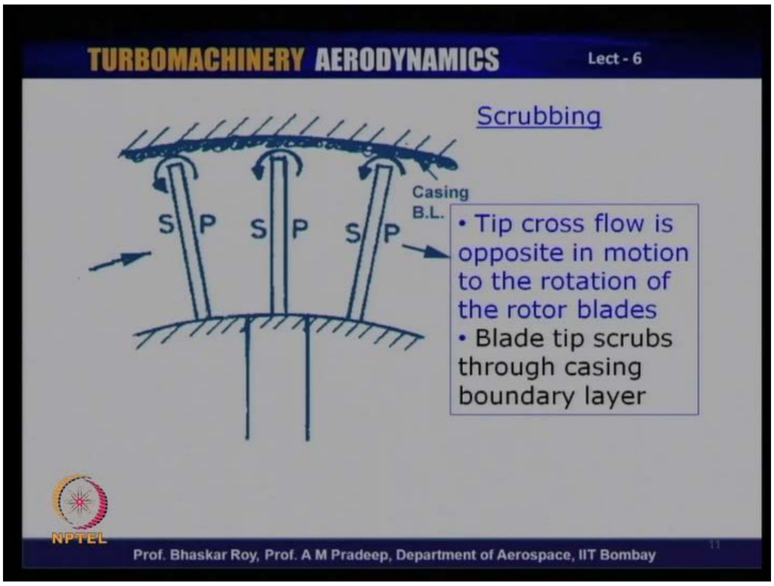

Let us look at another problem. The flow, as it goes through the blades, you remember, we are talking about, to begin with, blades that are rotor blades, these are rotating blades. Now, in this picture, as you can see, the blades are rotating; one side of the blade is what we call pressure surface, the other side is the suction surface. The normal fluid mechanics tells us, that over the open tip, the flow would move from pressure surface to the suction surface through this open tip of a rotor.

Now, this is inevitable again, following the fundamental fluid mechanic laws. Now, this tip cross flow is inevitable; but in a compressor, as you can see in this diagram, the blades are rotating in this direction, the cross flow is in this direction. So, the cross flow is in the opposite direction to the rotation direction of rotation of the blades; so, it opposes the motion of the rotation of the blade.

Now, this cross flow, again, normally occurs partially, definitely partially through the blade tip boundary layer, of the casing boundary layer. You see, when the flow move from this side to that side, there is a boundary layer which is been formed in the casing, so, part of this cross flow or sometimes whole of the cross flow, actually goes through the boundary layer to the other side.

Now, boundary layer of the casing, as you know, is essentially a low energy fluid, whereas cross flow, by virtue of a pressure differential of the two sides of the blade, often has high energy. So, this high energy cross flow penetrates through this low energy casing boundary layer and moves into the other side of the blade, which is the suction side of the blade. Now, this cross flow, essentially, then is a loss making position again, because the energy carried by the cross flow is irretrievable and it not available to the process of compression.

Now, as the blade moves through these boundary layers or the casing boundary layers, quite often the blade tip gap is so small, it depends on the mechanical capability of the manufacturing; and quite often, it is in the modern gas turbine engines, compressors, it is so small that the blade is indeed operating within the boundary layer of the casing boundary layer. And as a result, the blade is actually chopping through the boundary layer; this process has been called scrubbing. So, the solid body of the blade actually scrapes through or scrubs through these boundary layers and the cross flow fully, wholly goes through these boundary layers from one side to the other side in the modern axial flow compressor.

So, this scrubbing or scraping and the cross-flow together, are all loss making propositions fluid mechanically, aerodynamically in the sense, the energy lost in the process is not useful for the process of compression. So, this boundary layer that we see of the casing has another problem, that the tip of the blade scrapes or scrubs through this boundary layer it has, of course, a very small benefit of this scrubbing; that means, in a multistage blade, if you can go back to the earlier diagram, in a multistage blade, if a certain amount of boundary layer has been created, this rotor, when it is moving in a rotational motion, it scrubs through this casing boundary layer and it actually chops of the casing boundary layer.

So, the rotors do have, through the process of scrubbing, a chopping motion and it can chop off the boundary layers so that, immediately, the earlier boundary layer is partially chopped off, but this particular rotor and stator will again develop its own boundary layer. So, the process of boundary layer development through the multistage axial flow compressor is indeed, as you can see, rather complex; it does get chopped off, it gets scrubbed off or scraped off, but it develops again, because of the adverse pressure gradient. So, this development and chopping and scraping is continuous process through the entire multistage axial flow compressor through rotor stator, rotor stator and it is another complex process. However, this process is not useful in the sense; they are not useful to the process of compression. So, the energy that is lost in these things, are boundary layer development and chopping or scrubbing, are not useful to the process of compression. So, this is what three-dimensionality of the flow indeed creates inside the axial compressor blades. Let us see the other issue that indeed happens when a flow goes through a multistage compressor.

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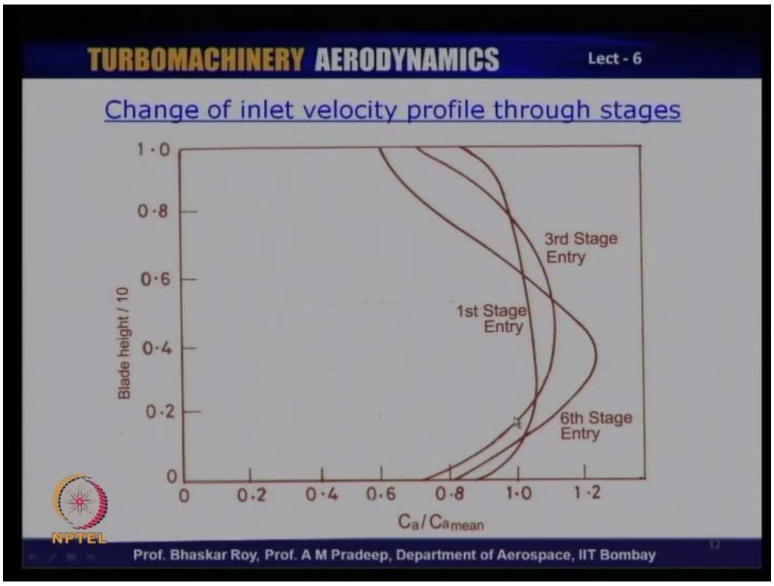

The diagram here tells you, that the inlet velocity profile through the stages changes in a multistage compressor substantially, because of all the things that we are talking about in the last half an hour or so. The flow then, you see, if it is the first stage; this is the first stage entry; so, the middle portion is relatively, you know, uniform. Then, in the third stage, it is become, like almost like a D. And then, by the time it is on the sixth stage, it is got hugely skewed; you see, it has lost uniformity hugely, because of the three-dimensionality of the flow that we are talking about, and the boundary layer development, and not to speak of the various control that are given to the hub and the casing; those controls, we will talk about later in this course.

So, the flow then, through the process of going through the multistage compressor, acquires inlet velocity profile; we are talking about the actual velocity profile, the x-axis here is actual velocity and it acquires a hugely skewed velocity profile in the later stages of a multistage compressor from hub to the tip of the blade; so, this again, creates a three-dimensionality. You see, we earlier, we were talking about the flow going in is uniform and then it acquires three-dimensionality. Now, we can see, that in the later stages of an axial flow compressor, the flow going in itself is already skewed, it is already non-uniform. And hence, no wonder that it will create a lot of three-dimensionality as it goes into the blade rows.

So, three-dimensionality of the blade and the three-dimensionality of the flow has a number of reasons and number of initial conditions over which the three-dimensionality is developed or grown. So, inlet velocity profile is indeed one of the components or one of the factors that contributes to the development of three-dimensional flow through the blade rows. We can summarize what we have talked about in terms of few words.

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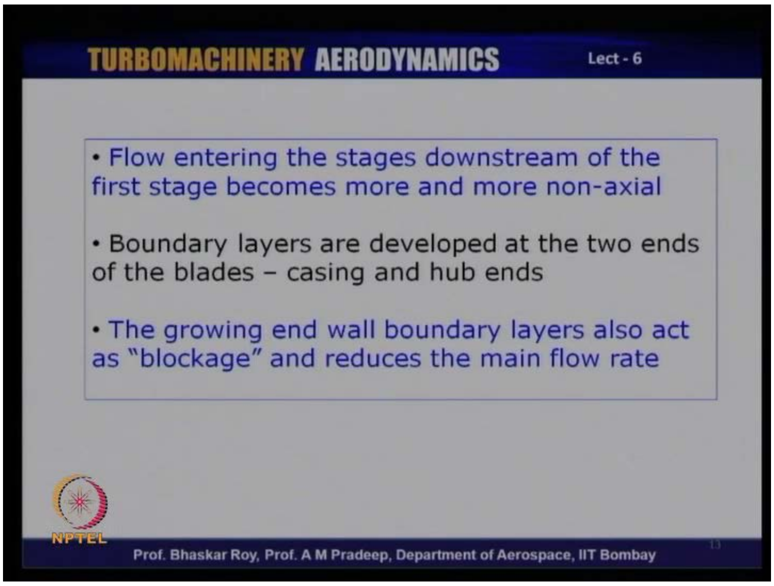

Flow entering the stages, downstream of the first stage becomes more and more non-axial; indeed, it has strong radial and tangential components. As we have seen, the boundary layers are developed at the tow ends of the blades, the end wall boundary layers as they as have commonly called; the casing boundary layer and the hub boundary layers. The growing end wall boundary layers also act as blockage, as we have just discussed, and has a strong tendency to reduce the main flow rate, which of course, as, you know, has a repercussion on the jet thrust creation of a typical jet engine.

So, these are the salient features that happen when you have three-dimensional flow. Let us now put together all the things that we have discussed in terms of very simple pictures.

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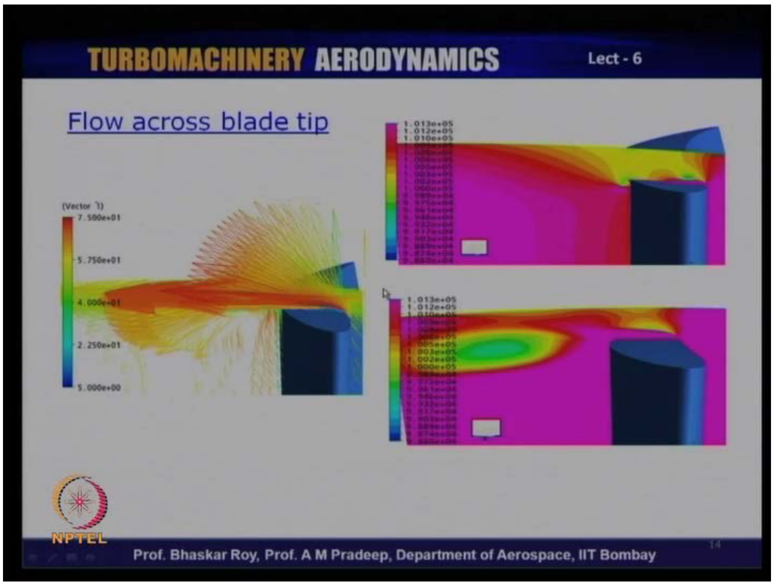

Now, these are picture graphs from computational dynamics, which we will be talking about later in this course. It simply shows what happens to the flow as it is passing across the blade tip. The flow actually moves over the blade tip from this side to that side, and in the process, it creates, as you can see here, this is near the leading edge of the blade, a little further down over the blade, this flow has now moved into the blade passage and the tip flow actually has short over and essentially has created a huge vortex system, which again, over contributes or at up to the passages vortex, that we have studied earlier.

So, it starts off with creating a cross-flow, and then this cross flow develops into a shooting flow, which then creates a passage vortex or a tip vortex, as it is often known. This vector diagram clearly shows that the flow shoots through the blade passage and it indeed, sometimes it goes almost which nears the next blade; the shooting is so strong in the modern at actual compressor. So, the vector diagram shows that the blade flow from one side to other side would indeed shoot through the blade passage between the two blades, from the one blade to another.

If we see this picture graph now, again from CFD, we can see here creation of the passage vortex on the other side of the blades.

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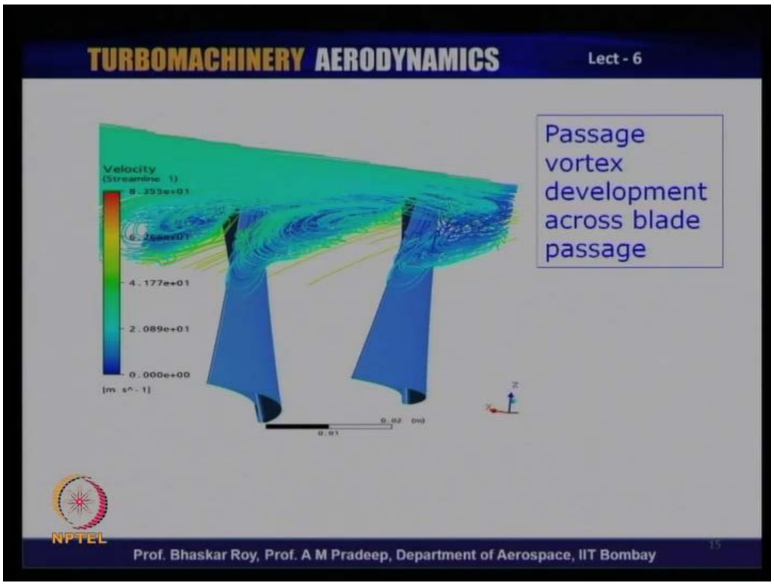

So, the flow that moves from this side to that side, it merges with the upper passages vortex; we had seen that two passage vortex may be created. The upper passage vortex matures that with the tip vortex of the tip flow, which creates the vortex of its own, and then, the two of them matured, and as the result of which, as they come out, it comes out with a stronger passage vortex. So, this passage vortex development has been captured in this CFD picture graph.

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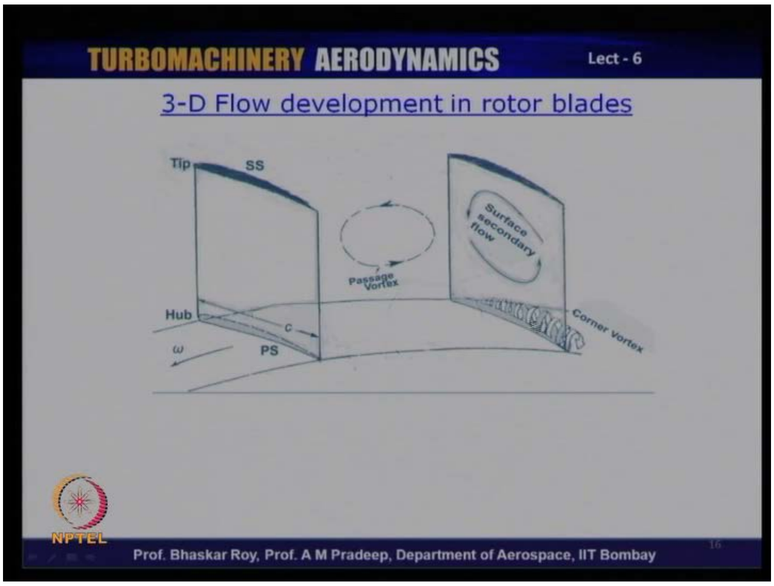

Let us now summarize what we done through simple pictures. Initially, the flow goes to the blade and it simply creates a passage vortex; it also develops surface on the surface of the blade, secondary flow features that we seen in the earlier slides and this secondary flow have the passage vortex are intrinsically connected to each other. At the corner of the hub over here at the root, indeed, there is a corner rotation; indeed, as you know, any fluid mechanic will tell you that whenever you have a corner, solid body corner, a corner vortex tends we created. So, corner vortex is created near the hub, is inherent to the geometry of the blade shape.

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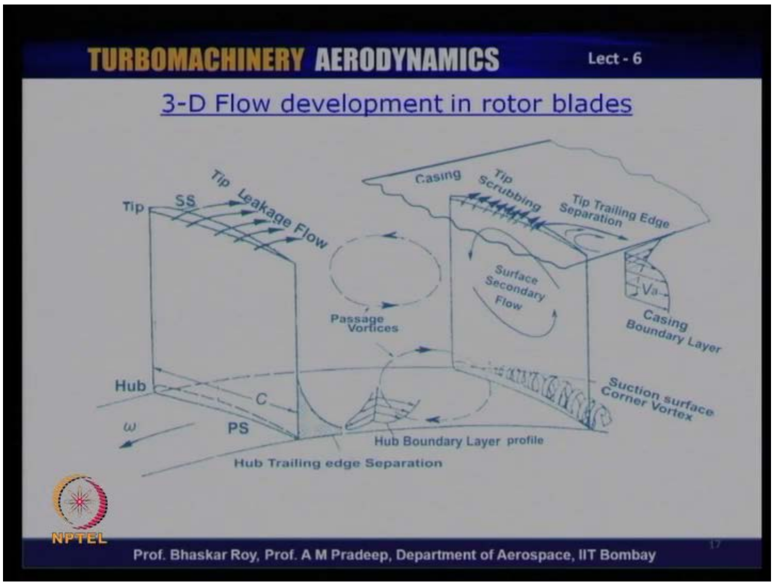

The next step is to understand, what are the other things that are happening. Now, this is the surface secondary flow that we saw; this is the passage vortex that we saw. Now, we can see that we have another passage vortex that is created below. And then, you have the casing; on the casing, we have the tip scrubbing that we were talking about; and then we have the tip leakage flow which we were talking about. The flow shoots from this side to that side; and then you of course, you the corner vortex, as yet. And on the casing, in not only you have the tip scrubbing towards the twilling edge of the aerofoil at the tip, you have casing boundary layer development. And a resulting in, a quit often, a tip trailing edge separation and a tip trailing in vortex system, which often called the tip vortex system.

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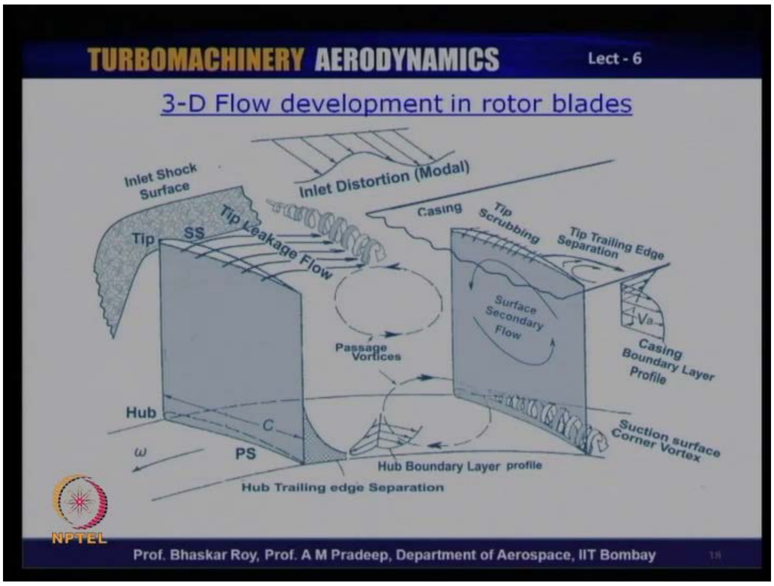

So, all these gets created as the flow passes through the blades. The next stage that we can see is, all of it put to gather. You have the tip leakage flow shooting through and creating a tip passage vortex or a tip vortex which may merge with this upper vortex over here; and, by the time it comes out, it may be one single strong vortex. And then. you have other vortex system down here, you have casing boundary layer, you have the hub boundary over layer here, you have the suction surface corner vortex over here and you have the tip trilling edge separation vortex system over here. All these would get substantially compounded, if the flow is indeed supersonic at the tip, which would create a shock surface and that would compound the flow situation. And then, as we saw, the flow could be distorted on non-uniform, going into the blade. This distortion shown here is a circumferential distortion; the earlier one we saw was a distortion or non-uniformity from hub to tip.

So, you can have non-uniformity coming in from hub to tip or you can have the distortion circumferentially which also contribute to the three-dimensionality of the flow going through the rotor blade. So, as we can see now, the flow going through these blades, it is indeed impossible to predict exactly what is going to happen, even when you are designing the blades. So, the design has to be followed up with intense analysis; to begin with, a lot of CFD analysis, which often feeds back into the design.

So, quite often, you have a design CFD feedback loop before the design is frozen or finalized, through those CFD and later on, sometime, do a lot of full scale stage testing, we try to understand the three-dimensionality of the flow. So, as you can see, we have a lot of complex aerodynamic situations inside the blades that needs to be understood to get better and better aerodynamic design of the blades and the blade shapes.

In the next class, we will be looking into this three-dimension flow analysis and we will start off with some very simple radial equilibrium theory, trying to capture some of the simple aspects of this three-dimensionality. And, moving forward, later on, we will do more complex three-dimensional radiant equilibrium theory. But in the next class, we will start with a simple three dimension flow analysis and a simple radiant equilibrium theory, which tells us in a very simple manner, how the three-dimensionality of the flow may be captured in simple mathematical form. This is what we will do in the next class.