Turbomachinery Aerodynamics

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Lecture No. # 17

Design of Compressor Blade: 3D Blade Shapes of Rotors and Stators

We are talking about axial flow compressors and axial flow compressor design in this lecture series on Turbomachinery Aerodynamics. Design of axial flow compressors, more specifically, the rotors, stators require a certain amount of understanding of how the flow actually flows over the blades. So, we have gone through the theories of those flow of the blades, the two-dimensional nature of the theory; we also had a look at some aspects of the three-dimensional flow, how the flow indeed becomes three-dimensional and how to track it; that is one of the bigger problems. One of the things we mentioned, is that, much of the three-dimensional flow analysis these days is done, indeed, with the help of computational fluid dynamics. And, as I have indicated, we shall be doing certain amount of Computational Fluid Dynamics, CFD , towards the end of this lecture series, where, we shall introduce to you certain aspects of CFD , as used in compressors and turbines.

So, we will continue to mention CFD as we go along and, some of it, probably, hopefully we will get clarified when we actually cover those in lectures later on in this course. At the moment, what we are looking at is, axial flow compressor design. Now, as we have seen, the actual flow compressors are indeed created with the help of aerofoil shapes. Now, all modern axial flow compressors - rotors, stators, fans in turbo fans, they are all made of airfoils shapes, and this airfoil shapes have been created essential to created to certain aerodynamic requirements.

Now, originally, many of the airfoils shapes were created by various agencies like NASA, previously as it was called NACA or the British Airfoils were created by royal air force or the German airfoils were created by Cardigan University; similarly, they were quite of few airfoils created in USSR or Russia. And now, many of these airfoils were used in the early era of compressor design, because they have carried with them, certain characteristics. Now, those characteristics are normally given in terms of their lift coefficient and drag coefficient; that is C l and C d characteristics, with reference to the change of angle of attack or what is more known as C l alpha or C d alpha characteristics of these airfoils.

Now, very soon it became clear, that for use in compressors and, indeed in turbines too, test the airfoil characteristics, per say, is not really sufficient and indeed, actually, not very useful; what is required is cascade characteristics. Now, we have done the cascade theory, and so, what is required is airfoils arranged in a cascade. The moment you have airfoils arranged in a cascade, number of other geometrical parameters come into picture.

So, not only the airfoil shapes itself, but how they have been arranged, the blade setting angle or what is known as stagger angle, the solidity or the spacing between the blades; all those things start coming into the picture and indeed, of course, the entry, mark number, Reynolds numbers, which are the aerodynamic parameters. So, number of geometrical and aerodynamic parameters put together, then, create what is known as the cascade situation; and then, of course, you have a arrangement of airfoils, which is, what is indeed, is the first building block of compressors and turbines. So, that is what, is initially required to start designing compressors.

Now, again, a lot of cascade data was indeed created by the early researchers, again from NACA and as I mentioned, many other countries had their own research bureaus. They created this cascade data based on cascade tunnel experiments; we have mentioned to you what cascade tunnel is. And, those pain-taking reports put together, cascade characteristics data were used for many, many years for designing of axial flow compressors, rotors and stators.

Now, cascade, of course you can use either for rotor or for stator, because cascade is a stationary arrangement. And, how we use it for rotor and how you use it for stator is your judgment and your prerogative as a designer. Now, many of these things are going on for, you know, almost half a century. Now, over the years, it has been realized that, what you create out of the old fashion early cascade data is reliable, very reliable, but they have some limitations of their own.

As we have done in the earlier lectures, the compressors are gone high subsonic, they have gone transonic; indeed, they are pushing towards high transonic and there are special applications where you could actually go supersonic. The entry mark numbers to many of the rotors, relative mach numbers have indeed gone supersonic. Now, moment you have that kind of low situation, you need cascade data for those situations, and more and more modern designers find that that kind of cascade data is no readily available at hand, in which case they would need to either extrapolate the earlier data or create their own data to initiate the design process.

Now all this is based on aerofoil arrangement in cascades. There are two things; one is, airfoil is by definition, is a two-dimensional entity is a two-dimensional aerodynamic shape. That aerodynamics is found more than hundred years back, to have huge aerodynamic efficiency; that means, its lift to drag; C l to C d ratio can be manipulated or can be selected in such a manner, if it is your requirement. And C l by C d ratio, indeed, actually is a figure of merit for airfoils choice and it effectively defines the aerodynamic goodness or badness or aerodynamic efficiency of a particular airfoil.

When you put them in cascade, it has been formed; the original airfoil C l C d characteristics does not, you know, carry on anymore, and so cascade value of C l C d for the same airfoils is often different, quite different depending on the cascade arrangements. So, the C l C d values that one gets of airfoil a characterization is not quite valid for cascade arrangements, various kinds of cascade arrangements and indeed they would need to be looked at afresh.

So, many of the early designers did create the cascade data and then later on, more and more modern designers have resorted to creating the data using CFD. So, they create the data in CFD, they often create the cascade geometry in CFD and then take it to the rotor design. Now there are two problems; one is cascade, as we all know, is a two-dimensional entity, it is a flat arrangements of airfoils, which indeed, are also flat airfoils, flat entities. So, whole thing is on a two-dimensional plane. Now, what happens is, a rotor or a stator is arrangement in an annulus plane. So, when an aerofoil is put there, it is rotating in an annular path. So, there are two things happening; one is, the airfoil is subject to flow, which is not really flat or two-dimensional; we have seen that the flow can be termed as a meridianal flow, which could be in a curve linear path.

The second is of course, in a rotor arrangement, it is a rotating airfoil. So, every airfoil then, in a blade from root to the tip of the blade, is actually rotating; they are not stationary; whereas, cascade data that is generated is stationary data. So, these two differences did always pose a little bit of challenge to the designers, that they had to make necessary changes in the cascade arrangement, airfoil arrangement to meet the annular, to begin with the annular requirement and then to meet the rotating requirement.

We shall go into some of these geometrical and fluid-mechanic, aerodynamic related issues in today's class to figure out how the blades are created, how blade shapes are created. So, as we see now, that the requirement is that, you create a blade shape, finally to meet the requirements of a rotating rotor or a stationary stator in a multi-stage axial compressor arrangement. And remember, both rotor and stators are indeed arranged in a annular space; so, all rotors and stators are arranged in a annular space, they are not flat arrangements.

So, these two differences have given rise to the feeling, and indeed, technology by which the blades need to be created which fit into this annular space and of course, at the rotor, is rotating entity. This is given rise to the three-dimensional blade shapes, you cannot afford to have the two-dimensional pure airfoil based entities; because, what happens is, once you are in annular space and once it is rotating, the aerodynamics creates three-dimensional flow.

So, whether you will like it or not, the flow situation with reference to the blades is highly three-dimensional. Once it is three-dimensional, many of the two-dimensional aerodynamic assumptions, aerodynamic understandings based on airfoil and cascade theories need to be slightly changed, need to be slightly revised. And these revisions, depending on the blade shape and depending on the blade size, depending on the ratio and indeed depends on the mach number and other aerodynamic parameters.

So, modern compressor designers have gone for blade shapes that are indeed, highly three-dimensionally in notion shape; and notionally, it is kind of understood that, if you make the blade shapes three-dimensional, it is probably possible to keep the aerodynamics of the flow closer to the two-dimensional theory with which we are comfortable with, which is understood and very well predictable from two-dimensional theories.

If you allow the flow to become too much of a three-dimensional flow, there is a strong possibility that much of the predictions or the predicting methodologies would fail; and in which case, the compressor would behave in a manner that is not predictable. So, a modern notion is that, you create a blade which is three-dimensional and then you are closer to the 2D or pseudo 2D blade theory that we have done in some detail.

On the other hand, if you keep the blade more with two-dimensional stacking of airfoils, the flow would indeed be three-dimensional and you would lose track of what is happening, and the predictability of the compressor performance would indeed go down. So, on this notion which is developed to a last 20, 25 years, modern designers tend to make the blades highly three-dimensional. We always know that, we already know that the blades are twisted; all compressor turbine blades are indeed twisted, rotor and stator blades are twisted, so twist is inevitable. We are not talking about twist at this moment, we are talking about some other geometrical parameters that bring in three-dimensionality to the blade shape; and in today's lecture, we will be talking about three-dimensional blade shapes.

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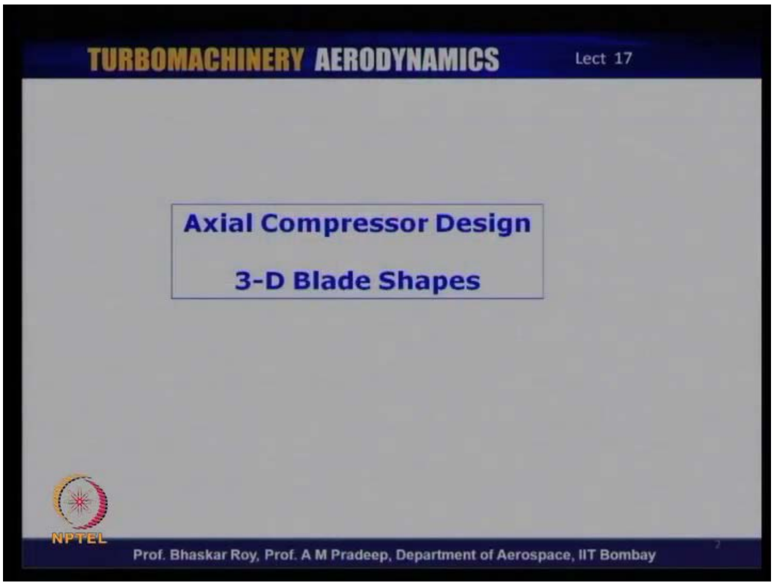

Let's look at some of the issues that are involved in creation of 3D blade shapes and we will start with how a two-dimensional blade is indeed, to begin with, created.

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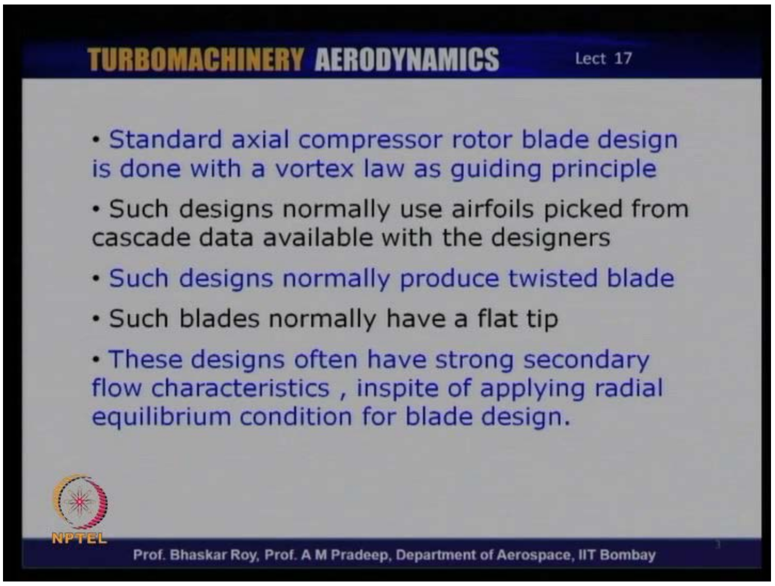

What happens is, a standard axial flow compressor blade shape is done with the help of some of the vortex law starting with a free vortex law, which we have done in great detail as the guiding principle. Now, that allows you to gated to the three-dimensional change in aerodynamic parameters. When you do that, the twist automatically comes into the shape. So, twist is there, even in what is called pseudo two-dimensional design methodology.

Such designs, as we were discussing, essentially use the airfoils which are picked from available cascade data and these cascade data have been very pain-takingly put together by various researchers. They carry data with reference to change of geometry, with reference to the change of solidity, with reference to change of mach number etcetera; so, lot of cascade data is available for certain airfoils. If you are creating new aerofoil, cascade data would not be available; in which case, you would need to create some initial data, may be with the help of CFD and then get into the design, and then later on use more and more CFD and then rig test to perfect the design.

Now, as we know, any design that we do using the vortex law, creates the twisted blade. And, these are made of airfoils; even at the tip of a blade, of the rotating blade, you have a flat aerofoil and hence you get a flat tip. So, the aerofoil, as an entity, being used as an aerodynamic fundamental building block, creates a flat tip. So, even now, or till recently, most of the rotor blades indeed used to have or still have flat tips.

These kind of designs, as I mentioned, they are arranged in a annular space and rotors are rotating, they immediately create strong secondary flow characteristics. Now, we have studied this in earlier lectures, and in spite of applying radial equilibrium, which again we have done the theory of radial equilibrium, the secondary flow is inevitable in a compressor annular space; which means, the flow is not only flowing nice aerofoil setting, but it was all kinds of radial flow components that develop as it goes into the rotor, and those radial flows create passage vertices which we have done, and those are the secondary flow characteristics which take away lot of energy, which is been transacted and as a result of which the compression job that is being done, goes down. So, secondary flow actually reduces the compressor efficiency.

So, these are some of the issues that are connected with standard or normal design procedure, which do produce in our reasonable good compressors; but if you want to have more modern compressors, which are also reasonably efficient compressors, competitively efficient compressors, you probably need to look at beyond this standard aerofoil based, cascade based design procedure, and that is what we would try to indicate in today's lecture.

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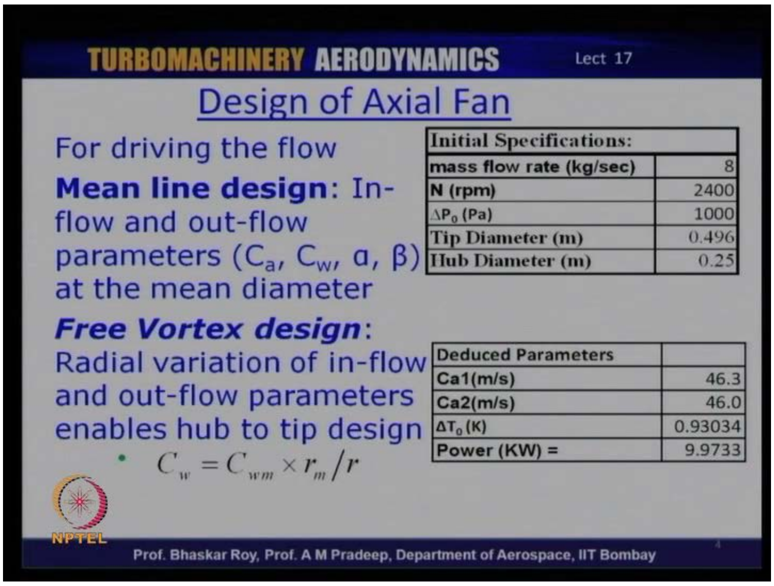

So, let us look at first, a very standard design procedure. What happens if you are designing an axial fan or compressor, is that you need some initial specifications; you need the mass flow for which, let us say, it has to be designed. I have just put some values here and exercise, which we have done ourselves here at IIT Bombay. But, you need to put in your values over there, on the right hand side of the column, to initiate your design process.

So, first you need the mass flow which the compressor has to process or compress, then you need to select rpm as quickly as possible; we were doing fan, allow speed fan, so, the rpm is 2400; the modern compressors, as you know, rpm could be 10000, 15000 or even higher. Then, you need to choose a certain value of compression that you need to do or pressure rise that you need to accomplish. You need to start using your dimension of your compressor, the tip diameter and hub diameter; because, those come out of the overall engine configuration and overall engine specification. So, some of those things should start coming as early as possible for the compressor designer to decide is, aerodynamic parameters and then his geometrical parameters.

Correspondingly, out of the first few initial specks, what can be immediately deduced or the axial velocity through the annular space of the particular compressor stage under design. Then, exit axial velocity, which are mass flow based and density based using the continuity condition. And then, the corresponding temperature rise that you would need to have, innovatively had corresponding to the pressure rise that you are trying to accomplish. And, this temperature rise, of course, multiplied by Cp would give you the specific work done or specific work that needs to be done, which indicates the power that needs to be supplied. Now, this power in a gas turbine engine, as we know, has to come from the turbine. So, the turbine power has to be decided as to how much power needs to be supplied to the compressor.

Then we, first thing that is normally done is, you carry out a mean line design; that means, at the mean radius through the entire multi-stage compressor, you first complete the so called mean line design of all the stages; and then only you do the detailed design of each stage from root to tip. When doing the free detailed design from root to tip, you bring in the free vortex design law or any other vortex design law, so that you can transpose the aerodynamic parameters from mean to the tip and to the root; and this transposition requires use of one of the vortex laws. So, this is what we would do in a very standard design procedure.

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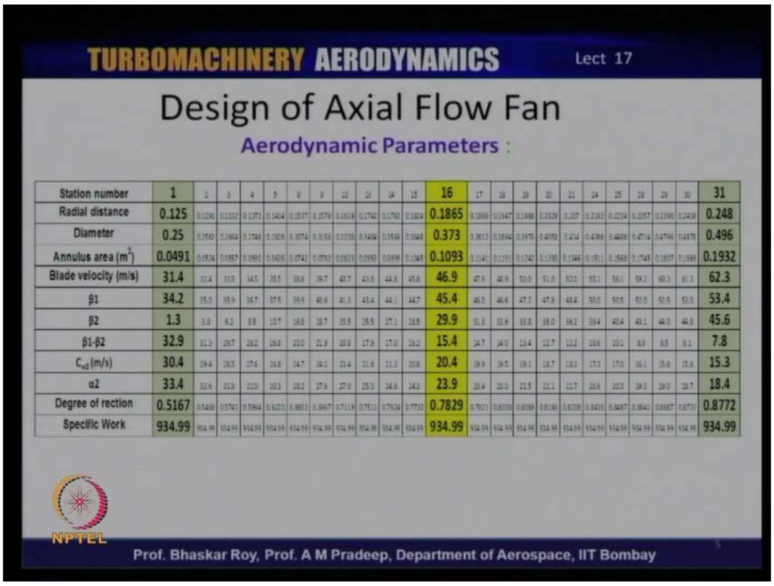

Now what is normally done is, the aerodynamic parameters that you need to use and you need to have for detailed geometric design of the blade, needs to be first found through aerodynamic theories or two-dimensional or pseudo two-dimensional theories; that, we have done in the earlier lectures. Now, here what I am showing is, particular rotor being designed and it is been subjected to elemental analysis over 31 radial stations from root to tip. So, it has 31 radial stations. So, 1 is the root and 31 is the near tip. So, that is the overall spread or the span of the blade over which the whole blade is being analyzed and moving towards the design.

So, those are the station numbers; that is the radial distance, corresponding diameter and then the annular space of each of those elements. And then, of course, all the parameters, velocity, the angles beta 1 beta 2 and the velocity parameters C w1, C w2 etcetera. And finally, the aero-thermodynamic parameter’s degree of reaction and specific work that comes out of this two-dimensional application of the two-dimensional theories.

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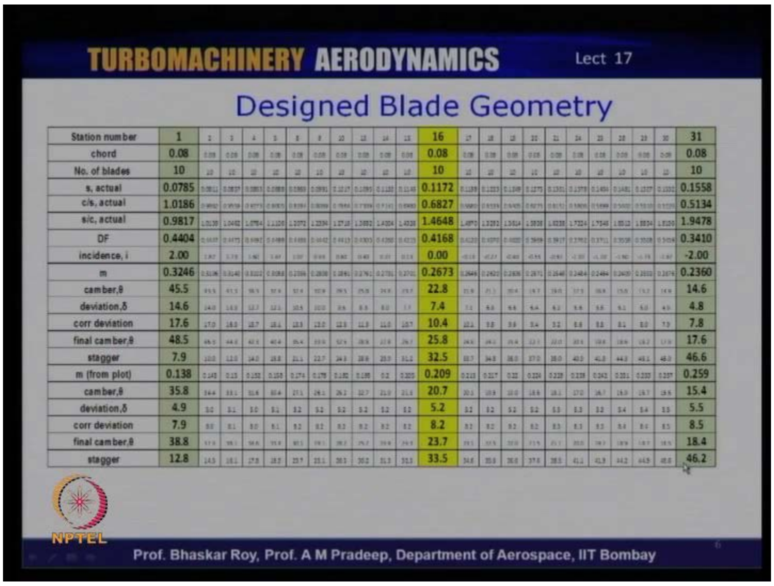

Now, once you do that, you get design blade geometry based on application of two-dimensional blade theories, in which you had the velocity diagrams, the velocity vectors the cascade arrangements at each of these 31 stations and all of that put together, start giving you the blade geometry. So, you get the chord length which you, sometimes may need to make a choice; it may not be an output, it may be your choice depending on the design that you are trying to accomplish.

Then, the number of blades which come out of the cascade theory and you need to make the number of blades, round integer; you cannot have fractions here. And, quite often, numbers of blades are decided in a judicious manner, not just a blind number that comes out of application of theory. And then, all the other parameters, the solidity, and then, of course, certain geometric or aerodynamic parameters like incidence; then deviation, which is an aerodynamic parameter of the blade. And then, certain iterative procedure is built-in, in which you apply correction. And finally, you get the deviation, and then the camber of the blade at every section. As you can see, the camber of the blade changes from 35.8 to 15.4 over a length of one single blade; so, one solid body of blade will have a 35.8 degree camber at the root and only 15.4 degree camber at the tip, and 20.7 at the mean, which I mentioned was designed first.

So, this change of camber produces the variable geometry blade from root to tip, and of course, we can see that these are also staggered at various angles 7.9 or 8 degrees near the root and 46 degrees near the tip. So, that produces the twist of the blade.

So, both the camber of the blade and the stagger of the blade vary substantially in a rotor from root to the tip, and that produces the twisted blade, and essentially, blade shape that varies substantially from root to tip. So, even, even in a standard design, you do have a large amount of change of blade shapes. So, final camber varies from 38.8 to 18.4 and final stagger, where all kinds of corrections are applied, varies from 12.8 to 46.2; so, that indeed would give you the twisted blade.

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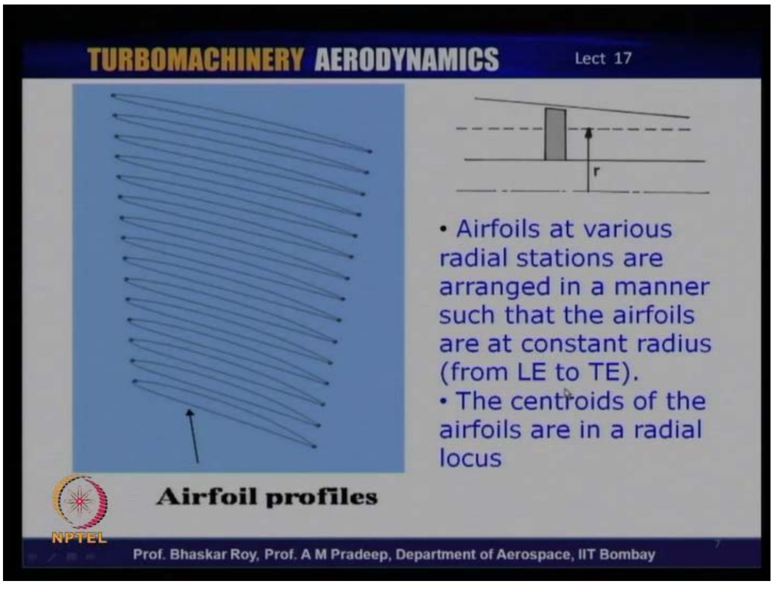

Now, let us look at how the airfoils are indeed arranged. What is done is, you choose airfoils at various stations, arrange them from root to tip; and these airfoils are chosen on the basis of the design that we just had a look at. So, each of these airfoils would have corresponding camber and each of these is set at a corresponding stagger, has comes out of that design exercise. Now, each of these airfoils, at this moment, are been set at a constant radius arrangement. Now, this is what we have done earlier; which means, aerofoil is a constant radius; aerofoil across the blade over here and that is what is been designed at the moment. So, you have a radius that is, r 1 here and r 1 2 here are same. So, this is what is been done at this moment of standard design procedure.

The other thing that is normally done is the centroids of all these airfoils are stacked up in a radial manner; so, they are all radically stacked. And, this radial tacking is a standard procedure, because it also scatters to minimal structural requirement; that means, the blades, if they are radically stacked, actually produces minimal amount of structural loading, the bending and the other loadings. If they are off the centroid or off the radius, they produce much more bending load; specially, as you know, when the blade is operational, the lift and the drag, essentially are active on the blade surfaces, and hence, radial stacking of the blades is a popular method by which normally standard design is done.

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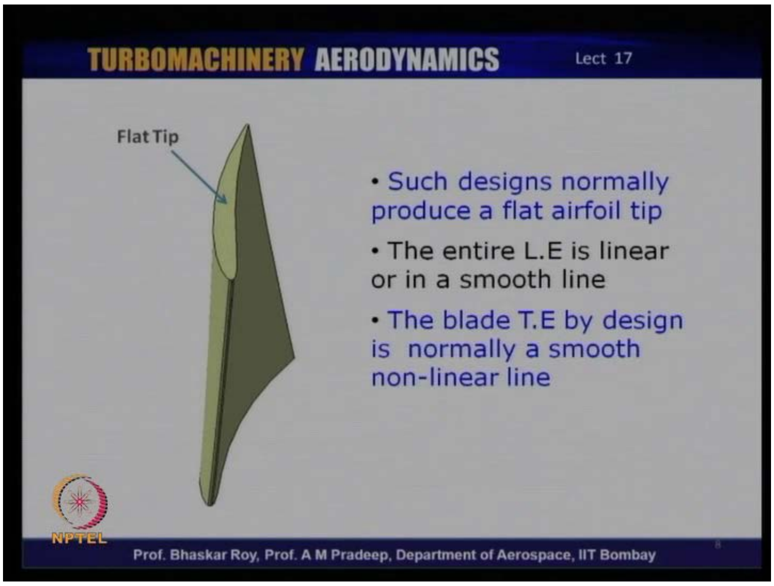

So, you get a blade which finally has a flat aerofoil tip. The entire leading edge; this is the leading edge; and the entire leading edge is linear and normally in a smooth line. Most of the time, it could be linear or it could be slightly curved, but a smooth curve, a very smooth curve. The trailing edge is by design again, needs to be a smooth curve; it may not be linear, it may be difficult to keep them linear. The trailing edge of the entire blade or the leading edge of the entire blade, you may try to keep one of them linear; the other would almost invariably become slightly non-linear. Now, this is what a normal standard blade design would produce. So, this much of three-dimensionality is built into even a normal standard blade design. In today, we are going, today's lecture, we are going to talk a little more about how deliberate further three-dimensionality is brought into the blade shaping.

Now this comes out of the fact that we have just seen, we have created a flat tip. Now, flat tip has a problem; the flat tip is inside a casing which is, you know, which is a curved casing now. Also, the flat tip is a stagger; this airfoil is at of high stagger. As we have just seen, the stagger of the airfoils is the highest. Now, if you have a flat tip, that is stagger, and then you have a casing, which is a covering, shrove; that is, invariably they are in compressors, the gap between the rotor and the casing from leading edge to trailing edge, then becomes a problem.

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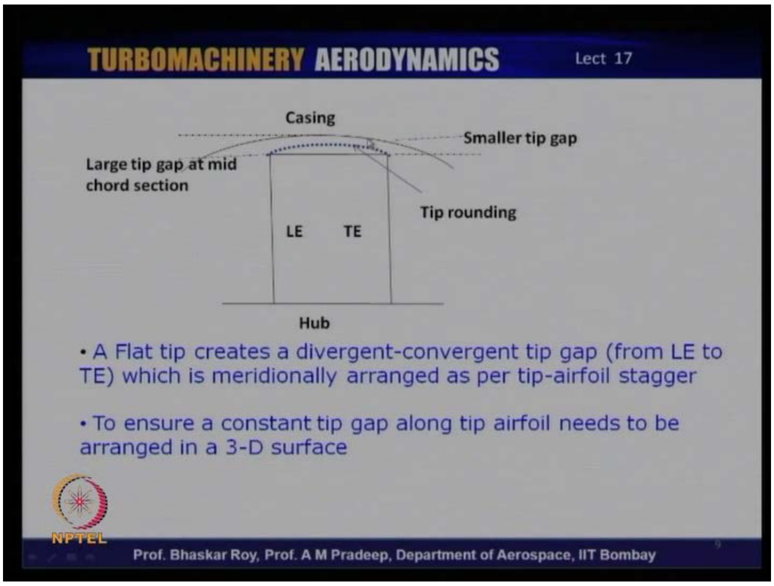

Let us look at this picture and see what the problem is. You see, what happens is, the blade over here, see you have a flat tip, and then this flat tip needs to be, you know, covered with the casing, which is in variably, you know, curved casing; and now, you have a situation, now this flat tip, we are looking at from a side, where this is staggered. So, this is at a stagger; now, it creates what is can be simply called, divergent-convergent gap, tip gap from leading edge to trailing edge.

So, so the tip gap is first divergent. So, at the mid chord, the tip gap is much more than at the leading edge and then it converges again to trailing edge to, lower tip gap. So, tip gap is highest at the mid chord. Now, this is a problem, because most of the tip flow from pressure side to section side, occurs through the middle of the chord, and as a result of this, this large tip gap at the mid chord, promotes large tip flow, and essentially, a large losses are accompanied in the compressor operation. Now, as a result of this, the tip loses the compressor efficiency, the tip related compressor stall or the instability becomes one of the big issues. Now, this indeed has been a big issue of the earlier compressor designs, because they were indeed susceptible to tip stall very easily, and one of the reason they are susceptible to tip stall is because this, that the tip gap was uneven and essentially was some kind of a divergent convergent gap, because of the use of flat airfoil at the tip, and the tip was amenable to early stall; and then, of course, instability in the compressor. To get around this, what the compressor designers have started doing now, is they create a tip airfoil which is arranged on this three surface, which let us say, could be parallel to the casing curvature.

So, first you need to figure out, after the blade has been primarily designed and the stagger is known, you can geometrically, from three-dimensional geometrical configuration, you can figure out exactly what this casing curvature is at that particular stagger and then try to mimic that casing curvature with a small gap to create the tip. This is the tip rounding that could possibly create a constant tip gap of the tip of the blade from leading edge to trailing edge. Now, that means, the tip airfoil is not a flat airfoil anymore, it is on a three-dimensional curved surface.

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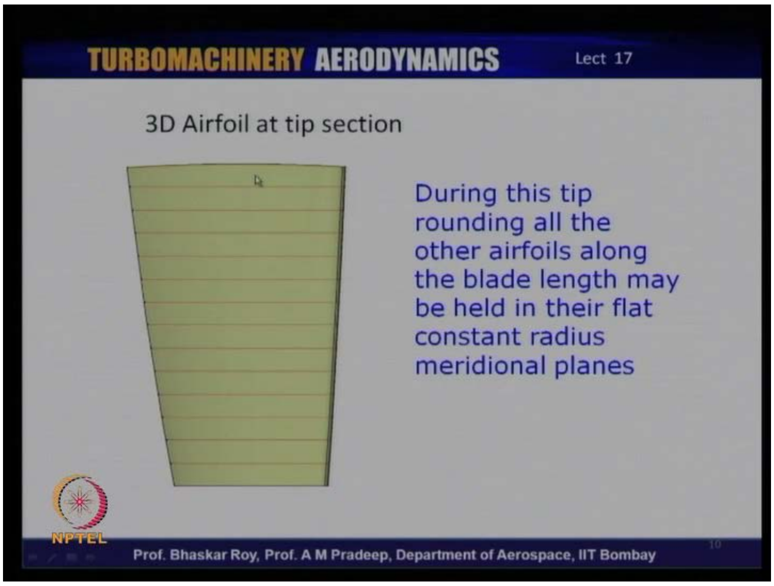

Now, this is what modern designers have already started doing the result, is that, you get what is known as 3D airfoil. So, the airfoils by definition, over hundred years, were two-dimensional entities; now, suddenly they have become three-dimensional entities. You need to have 3D airfoils, and during this tip rounding, one of the things, the first modification of, let us say, earlier compressor design; if you round out the tip, you may leave the other airfoils, you know, the flat airfoils that they were originally designed for, and only that tip airfoil is converted to a 3D airfoil and arranged or set at the tip to create, let us say, constant tip gap to get out of the tip flow related instability and stall problems.

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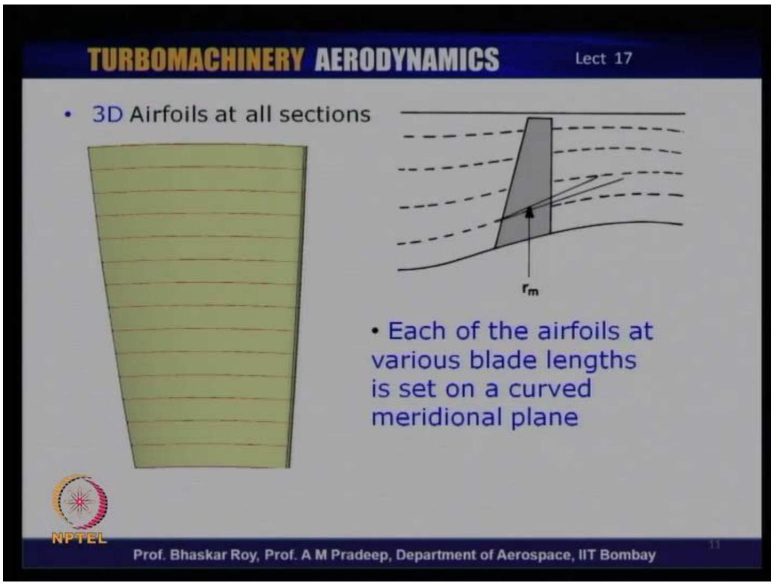

However, the more modern designers would like to see where all airfoils are essentially arranged in curvilinear surface. So, all the airfoils now, indeed all the way from root to tip, are three-dimensional airfoil. Now, geometrically you see it make sense, because, if you look at this picture, which we have seen before; this is the meridian path that we have talked about and this meridian path shows that it is not constant radius, radius here and radius here are different.

So, they are on a non-constant radius path from leading edge to trailing edge and quite often, they are on a curve path, slightly curvilinear meridian path; near the tip, it may be a little flatter, but indeed they are curvilinear. And near the hub of a high pressure ratio compressor, it could be hugely curvilinear near the hub; in which case, deploying flat airfoils over here is actually self-defeating, because the flow and the geometrical situation calls for use of three-dimensional airfoil or airfoil set on three-dimensional surface. Now, the other thing, quickly remember that always blades are on an annular space and they are arranged in a annular manner; which means, that if you take a cut annular, cut on any section, even a mid-section, what you would get is a circle.

So, the width-wise or laterally, the airfoils are also on a curved surface; it is not on a flat surface. So, not only longitudinally from leading edge to trailing edge, but also laterally from one surface of the blade to the other, the blade is actually on a curved surface. Now, as a result of this, the blades actually have become highly three-dimensional and the blades need to be set now on cylindrical coordinate system, not just xyz coordinate system.

So, setting the blade on a cylindrical coordinate system, so that they are arranged in a annular space, and then giving them a longitudinal curvature from leading edge to trailing edge creates, what is known as 3D airfoils and the modern designers have started using 3D airfoils, all the way from hub to the tip of the airfoil of the blade.

So, you need to create all of those blade sections that we had design to begin with, let us say, 30 or 15 or 20; all of them would need to be now recreated with 3D airfoils. So, original 2D airfoils available from cascade data and design data bands would need to be reorganized and reshaped into three-dimensional airfoil entities for deployment on modern blade designs.

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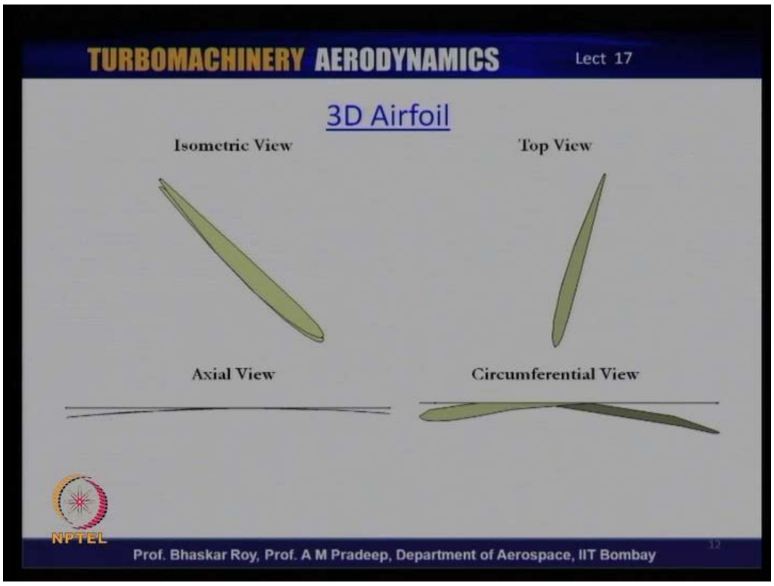

Let us look at what happens to this 3D airfoil very quickly. If you create a 3D airfoil, you see, a flat airfoil is flat; a 3D airfoil is been set on a curved surface. Also, once you create a 3D airfoil, it is indeed possible that the width-wise or the thickness-wise, distribution-wise it will changed. So, the two-dimensional airfoil had some thickness distribution, the moment it is arranged in a three-dimensional space, the two-dimensional shape would have to be altered if one has to conserve the aero-dynamic performance parameters; and as a result of which, it changes it is thickness or what is known as t by c distribution. Once that happens, you have a slightly different airfoil, and then the overall view, circumferential view; you would get an airfoil, which is like this.

So, this is your 3D airfoil, whereas a flat one would simply give you a straight line from the side view. So, this 3D airfoil needs to be created or recreated from an earlier 2D airfoil. So, this recreation process is often done with the help of CFD to begin with, and a lot of geometric modeling; it is, it is sometime results in iterative process, so that you get a 3D airfoil which meets your aerodynamic requirements.

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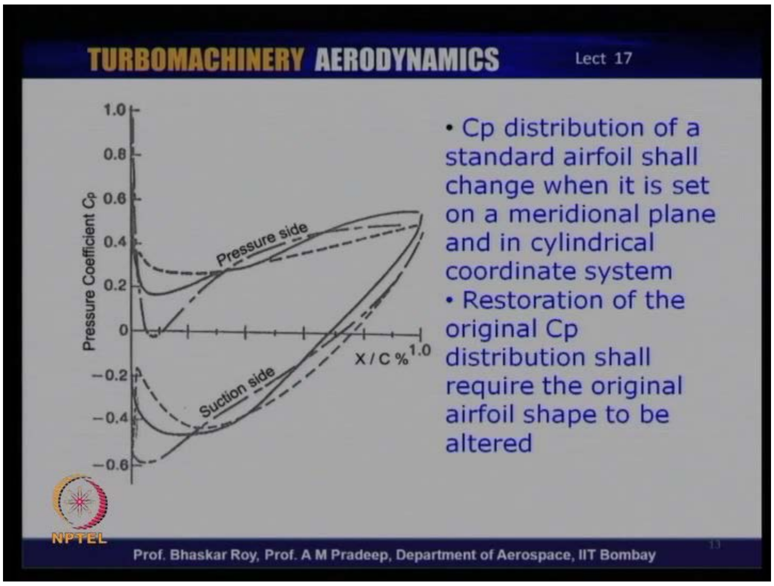

So, what happens is, two-dimensional blade has a certain Cp distribution. We have looked; we have had a looked at this kind of Cp distribution before. Moment you can change their blade and create it into a three-dimensional airfoil, this Cp distribution would change. Now, if you are happy with the earlier Cp distribution, which meets your aero-dynamic compression requirement; to restore the Cp distribution on the blade shape, you would need to alter the 3D airfoil shape in such a manner, that you get this Cp distribution back on your 3D airfoil. So, this restoration of the original Cp shall require original airfoil shape to be altered, all the way from leading edge to trailing edge. The Cp distribution would have be altered substantially. Once you do that, you have all kinds of other possibilities.

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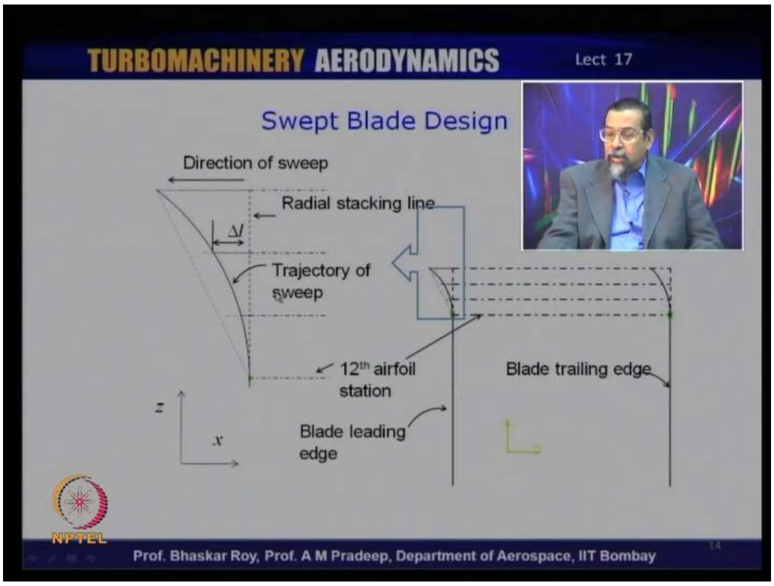

We have seen the blades are already twisted, we have seen blades already having varying camber from root to tip and we have seen they have differential stagger, substantially its different stager from root to tip. The next thing that modern designers trying to do, is use certain shapes like sweep, that has been used in aircraft wings for many, many years to gain certain benefit.

Now, what happens is, the sweep definition that is used in blade shaping is essentially something like this; that airfoils that has been created now, even after creating the 3D airfoils are shifted; so, the stacking line is not radial. We have said that stacking line was radial; even when we were creating 3D airfoils, the stacking line remain radial.

Now, we are saying that the stacking line may be shifted and the shift of the stacking line from a purely radial direction creates the sweep. Typically, the sweep is observed at the leading edge; of course, you can observe it at the trailing edge also, and this gives rise to the fact that the flow coming into the blade would meet the tip first and progressively lower down the blade, it will meet the other part of the blade later. Now, it is been observed very closely through CFD as well as through lot of actual tunnel rig testing, that the flow, when it is hits at tip first, actually traverse along the blade length and tends to have a inward flow, from the tip towards the midsection. This is a benefit because it uploads the tip; it overloads the mid section, but creates the offloading of the tip section.

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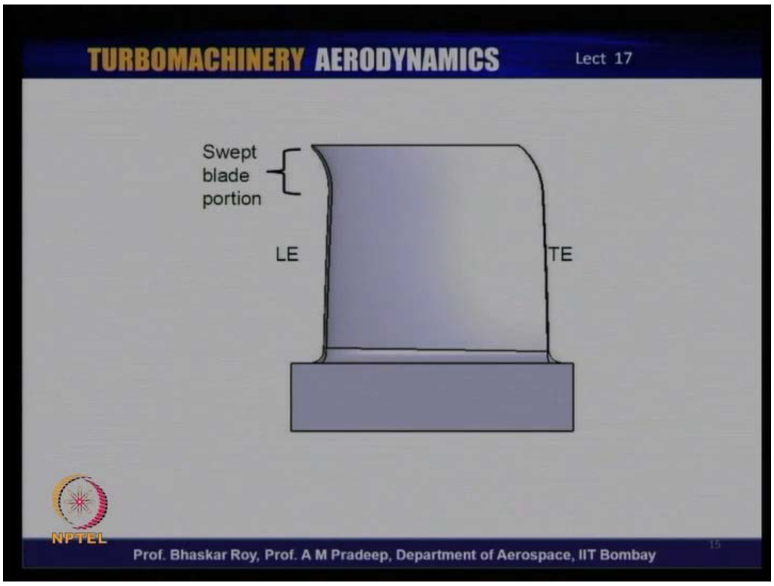

So, the sweep that is created, it can be at the leading edge, it can be also at the trailing edge; they may be differentially swept at the leading edge and at the trailing edge. Because, now, the stacking line is not radial over here; the amount of sweep given over the length of blade can vary depending on the design. Sometimes, the entire blade can be swept, sometimes only a portion of the blade is swept; it may be swept backward also, depending on the designers understanding of the three-dimensional aerodynamics of the flow and that comes out of CFD.

So, large number of design is now, essentially back by CFD and this CFD gives you a first cut notion; it is not the final thing, but it does give a very good first cut notion or what seems to be happening on the blade surface. And then, designer decides what kind of blade shaping he would like to prefer. So, the amount of sweep, the amount of portion of the blade that is to be swept, and of course the deployment of three-dimensional airfoil on these blades, essentially come out of large amount of iterative study between the designer and CFD analyst.

So, this iteration between design and CFD analysis, actually have speeded up the design, substantially compared to the early days; and as a result, we have far more complicated blade shapes these days, based on this kind of high curative design procedure. So, let us take a look at some more possibilities that do exist on the blade shape.

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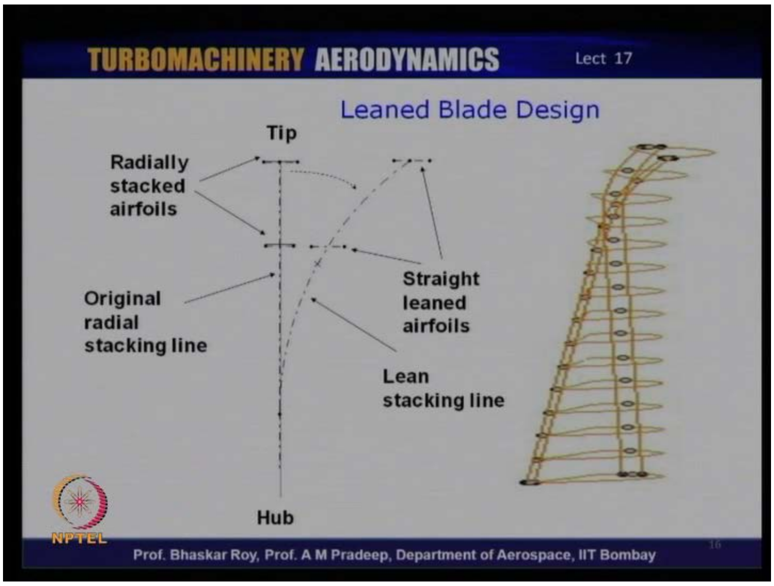

The next possibility is the, what is known as leaned blade. In, for aircraft wing designer, this would be called a dihedral. So, dihedral, in addition to sweep or without sweep, can be imparted to the blade shape and these blades are often called leaned, because they lean from radial stacking, either to in the circumferential direction; sweep, as you remember, the airfoils were shifted forward or backward. Now, the airfoils have been circumferentially shifted from the radial stacking, either on this side or on this side, and this creates the lean.

So, this is the lean stacking line, over which the airfoils can be… So, this was the original stacking and then you have the airfoils now, leaned like this and these are the airfoils. So, leaned blade stacking is the other aspect of modern blade design, in addition or alternate to the sweep; sweep or lean may appear together or they may appear separately. Many of the modern designs actually do have lean and sweep together in the modern blade shapes.

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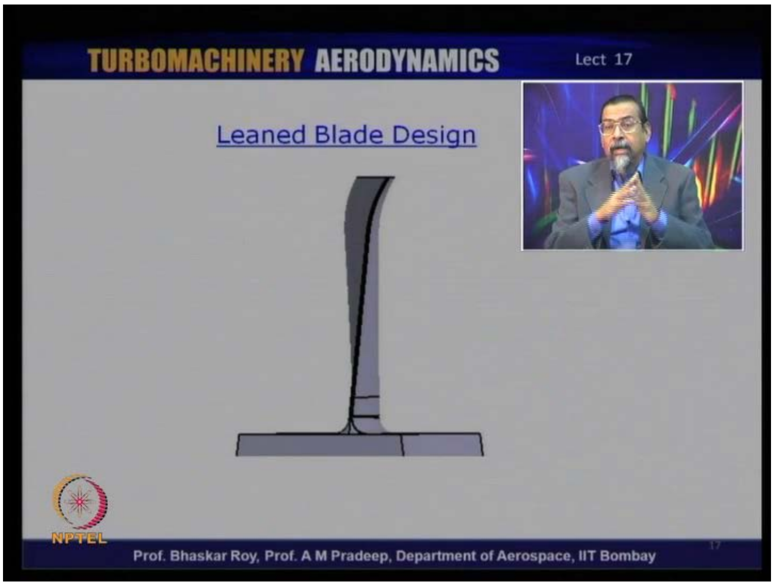

So, this is typically a leaned blade and it creates, at the tip, a lean that is different from sweep and as a result of which the blade acquires a highly three-dimensional shape. The problem to the designer is, you have airfoils there, you still have airfoils; and as a result of those airfoils, the moment you give that kind of shape, the intervening portion of the blade needs are interpolated geometrically through geometrical, three-dimensional geometric modeling. And then, often, when you give that kind of shape, it may get wrinkled; the surface may not be smooth. You need to get smooth surface, you need to arrive back at the smooth surface; blades have to have smooth surface on both sides.

So, when people create this kind of complicated blade shapes, you remember, blades are already twisted, they already have differential camber, and now you are giving sweep, you are giving dihedral, so, the blade surface become wrinkled. So, those are the issues that the designers will have to solve.

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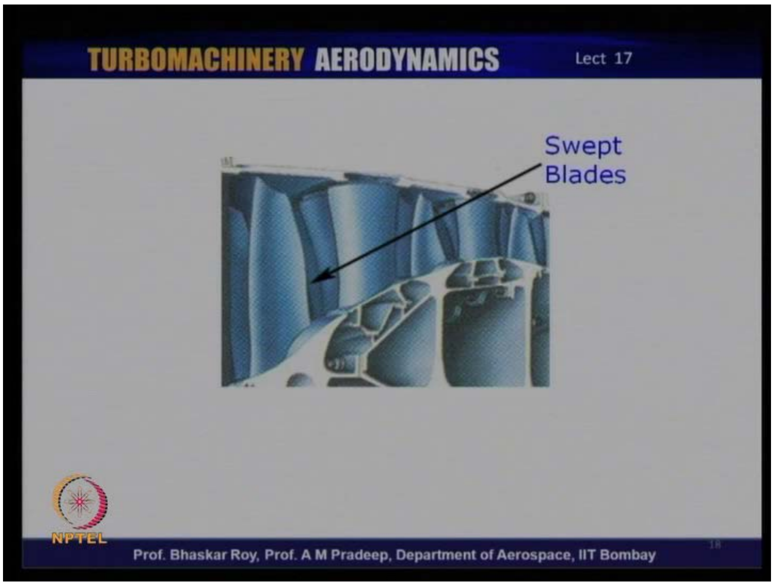

We can see here, some of the modern blades. These are indeed pictures of very modern compressor blades and we can see here, the leading edge is kind of curvilinear, certain amount of sweeps seems to have been given, which seems to be slightly backward swept over here. And then, of course, the blade is highly staggered, and as you can see here, it is rounded tip, which is of course a stator; you could probably, you do not see it here very clearly, but the rotor would also have a rounded tip and the rotor trailing edge may be slightly swept forward.

Now, we are seeing it from a side, so this is highly three-dimensional blade shape. We are actually not seeing the real blade-shape, we are seeing some kind of an angular side view. But, one can see that it is a highly three-dimensional blade shape, that we are looking at. If you look at the second rotor, you can see that the rotor is indeed carrying dihedral.

So, not only they are swept, they the leading edge is curvilinear trailing edge is curvilinear and they evidently have certain amount of dihedral. Same goes for the stators, you can see the stator leading edge has certain kind of swept forward; first it is straight, and then the leading edge is swept forward. On the other hand, trailing edge is more or less straight with the backward curvilinear sweep towards the trailing edge. If you look at the third rotor, it also has certain amount of dihedral and probably certain amount of sweep.

So, all the three rotors, and indeed all the three stators, actually have highly three-dimensional blade shapes, which is typical of modern axial flow compressors. So, that is the way a combination of aerodynamic analysis, geometric modeling, very intense amount of geometric model is required to get a smooth blade shape. Obviously, final aerodynamic of the blade would demand that you have absolutely smooth shape on both the suction and the pressure surface, from root to the tip of the blade. So, this is a first requirement of the final blade shape.

So, through aerodynamic studies, through CFD and through intense geometric modeling, you need to create shapes that are finally, aerodynamically acceptable and would evidently or presumably create very good performance. On the other hand, they meet prime of certain structural requirements, so that the blades are not structurally highly stressed. And then, of course, you need to be able to fabricate those blades, they need to be fabricable.

So, the fabrications state of art of the technology, would have to be deployed many of these blades as, you know, made of materials, which are titanium alloys and aluminum alloys; and sometimes, towards the end of the multi-stage compressor made of steel. So, you have to be ensure, that these intricate shapes can be very accurately manufactured. If you cannot manufacture them, then there is no point designing them. So, your state of art of material science and state of art manufacturing technology have to be factored in during the design process.

So, these are the issues that a modern designer would have to deal with, when he creates a modern axial flow compressor rotor and stator blade shape. (Refer Slide Time: 51:31)

Some very simple blade shapes that we can look at tell us, that you can have a fully slept blade like this or we can have predominately straight blade stacking. So, this is where you have a swept stacking. So, stacking is swept like this; this is a straight stack blade and that is why it is called a straight blade. As you can see very well, it is actually a twisted blade; it is no really a flat blade. So, it is not a flat blade, it is a straight radial stack blade. Whereas, this one is, stacking is curvilinear stacking; so, that tells us what kind of difference comes about in the geometric modeling of the blades in modern axial flow compressors and axial flow fans.

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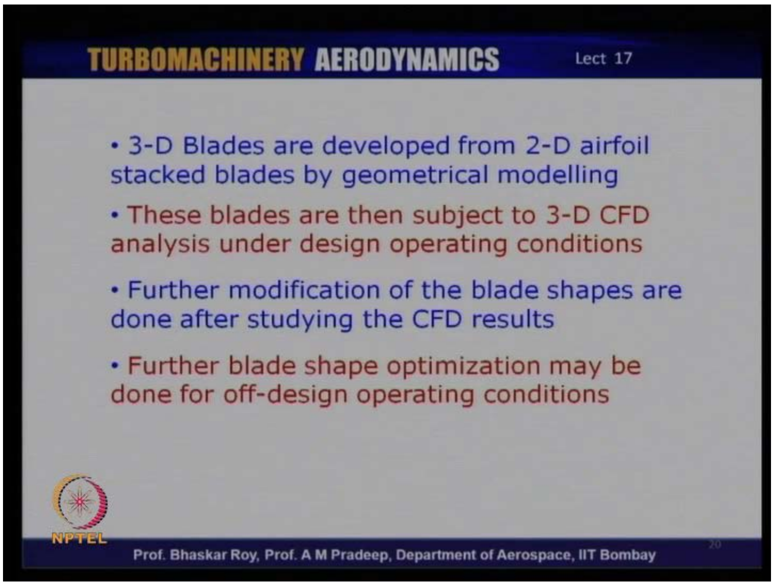

So, in summary, we can say, that the 3D blades are indeed developed or reconfigured or reshaped from earlier known two-dimensional airfoils, and then they are stacked by geometric modeling; modern blades are not stacked radially anymore. These blades are subject to intense 3D CFD analysis under design operating conditions. Further modification of the blade shapes are done after studying the CFD results.

So, if you have separation or deviation or related issues, the blade shapes would have to be very finely tuned to get out of those separation related problems, so that, under those situation, you have a stall or, you know, strong separation problems. Further blade optimization, quite often may be done for to gated to the off-design operating condition. All compressors would have to operate under off-design conditions, specially those which used in aero-engines. And, as a result of the off-design of for aero-designs is extremely important. So, some times, the blade shape is further optimized or redesigned or reshaped to gated to very good off-design operating efficiency. Otherwise, you may get a blade that is of very high design point efficiency, but may be poor in off-design. So, to counter that, many of the blade shapes are optimized to, gated to off-design operating conditions.

So, this is the intense procedure by which blades are designed, you have to have the... You still need certain amount of two-dimensional airfoil cascade data available with you, and when you put them together, you have a starting building block, then you have to start shaping your blade, you have to do intense three-dimensional CFD analysis, and then you have to do design point analysis, and then you have to start doing off-design analysis. When you put them all together, you have a blade that satisfies the requirements of the compression job that is being assigned to this blade under various operating conditions. Then, you have a blade that is good and it can go in a engine, that will go on an aircraft flying machine. So, these are the procedures for modern axial flow compressor and fan design.

We have come to the end of compressor chapter in this course. Next lecture, we will be talking about a problem, that is, on noise. This noise is a major problem these days; so, in the next lecture, we will look at the noise problem associated with compressor and fan operation; specially the ones that have gone transonic and supersonic. And, we will look into how those noise problems are countered or tackled during the process of compressor design.

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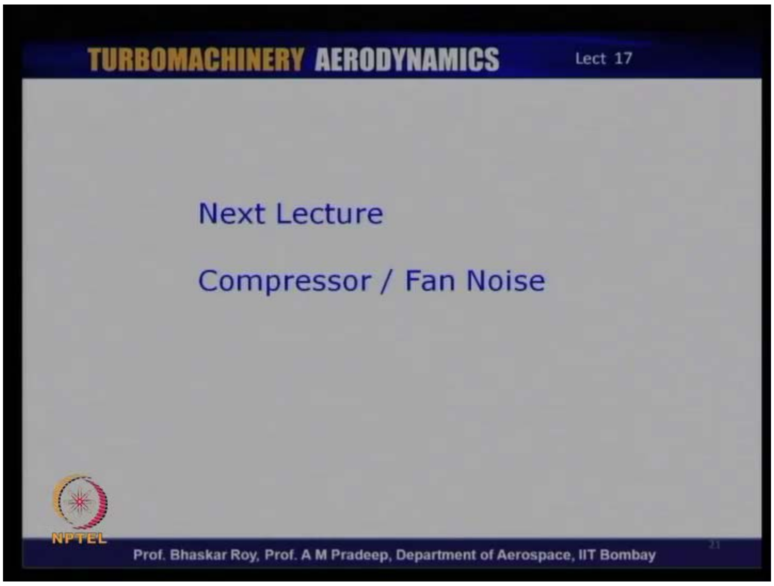

So, we have come to the end of the design lecture, in which we have tackled the two-dimensional design, we have tackled the three-dimensional design and it tells us that you have to go through a lot of process, iterative process by which you do the design. And the last thing that you would need to look at is, what we do in the next class; that is, look at the noise problem.

You have to design a compressor fan, which is not a noise making device, then it will not be certificated, it will not ever be used in an engine, it will never fly. So, design process would have to be finally ended by taking care of noise-related issues. We will do that in the next class.