Turbo machinery Aerodynamics

Prof: Bhaskar Roy
Prof. A M Pradeep
Department of Aerospace Engineering
Indian Institute of Technology, Bombay

Lecture No. # 29

Turbine Blade Design: Turbine Profiles, Airfoil Data and Profile Construction

We are talking about axial flow turbines. An axial flow turbine theory is the two dimensional theories, the three dimensional theories and a little good exposure to blade cooling that we have done in the earlier few lecturers. Earlier lectures have exposed you to the general technology and the aerodynamic theories behind the axial flow turbine operations.

Now, in today's lecture we will start with a discussion on how such axial flow turbine blades are indeed designed. Now, axial flow turbine blades just like axial flow compressors are essentially aerodynamic machines.

So, the fundamental principle based on which they operate are aerodynamic principles. We have also seen that just like compressors, the turbines essentially operate with airfoils as the fundamental building block.

So, we need some kind of airfoils, to initiate the aerodynamic activity which prompts the turbine to work, and in this case actually produce work compressors where work absorbers turbines are work producers.

Now, in case of compressors we use one kind of airfoils to put in work in the fluid. In case of turbines, we use another kind of airfoil to take out work out of the turbines. There are one or two examples you know, just one or two rare ones, where one can probably use very similar or almost same airfoil for both compressor and turbine. But, by and large, airfoils that used for turbine are significantly different from those used in compressors.

We shall also look at how the overall turbine blade is built up which we shall do in the next class. The three dimensional shape, we have seen that the compressor blades tend to be highly twisted and of course, they have very complex shapes sometimes. We have seen the basic design theory of turbine which often differ from the basic compressor design theories. In the sense, free vortex is not the most popular theory for turbine design or for that matter near free vortex. The turbine designers use here somewhat different theory like a constant stator exit angle alpha 2 from root to tip.

So, the basic design philosophy of turbines is also quite often different. Today we will look at the basic airfoil that have deployed in turbine and how those airfoils are indeed selected or designed or created to put in turbine blades. And of course, we have two sets of blades, we have the stators or stator nozzles as we call them, and we have the rotors which of course do the work.

So, we will look at various kinds of airfoils including transonic and even supersonic airfoils which have been used not necessarily in the commercial aero engines. But, in very special cases of turbines, gas turbines are supersonic blade profiles have been used and we will have a look at those. When we discuss those things, we will have a brief discussion on where and how those kind of blades are probably actually utilized.

So, in today's lecture we will be looking at axial flow turbine blade profiles. Now, designing the blade profiles is one of the issues that need to be looked at from a number of points of view. One of the points of view is that in the early days of design, the profiles were generated by various NASA or you know earlier Naka or various laboratories in various countries in England or in Germany or in Russia. There is various design bureaus mainly set up by government or respective governments and they created some families of airfoils which were used for compressors and for turbines rotors and stators.

However, later on people have realized over the years that what you need to do is not necessarily use the same airfoils again and again, but, you can indeed generate your own airfoils to suit your own needs.

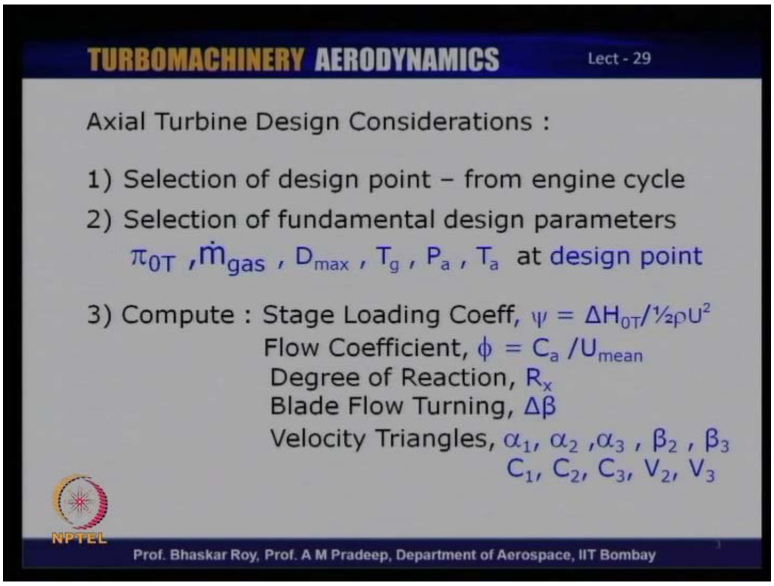
This of course, has brought in a lot of refinement and it allows the efficiencies of the turbines flow over the turbines to be very accurately predicted and accurately reflected in the design. This allows for very high efficiency turbine design in the modern gas turbine engines.

These of course, use the modern computational fluid dynamic techniques some of which we will discuss briefly in the final lectures of this lecture series. But, I will have a very brief mention of that in today's lecture just to complete the profile design discussion that we having today. This tells us that profiling today is not just a selection of a blade from a library or a catalogue, but, it is far more involved and probably requires a little more effort on the part of the designer to mesh or to work with the analysts who are probably the c f d people. Again you get into as we have done in case of axial flow compressors, you get into a design c f d analysis loop and this is inevitable in the modern blade design. So, that is something which will very briefly touch upon today, but, we will discuss in some detail later on in this lecture series.

So, we will start off with blade design and axial flow turbine blade profiles. Now these profiles as we know are made up of airfoils. So, the classical airfoils that people have used over the years are based on basic design philosophy.

Now, let us look at the basic design steps or design philosophy that one starts off or that kick starts the design.

(Refer Slide Time: 07:53)



TURBOMACHINERY AERODYNAMICS Lect - 29

Axial Turbine Design Considerations :

1) Selection of design point – from engine cycle
2) Selection of fundamental design parameters
π_{0T} , $\dot{m}_{gas}$, D_{max} , T_g , P_a , T_a at design point

3) Compute : Stage Loading Coeff, $\psi = \Delta H_{0T}/½\rho U^2$
Flow Coefficient, $\phi = C_a / U_{mean}$
Degree of Reaction, R_x
Blade Flow Turning, $\Delta\beta$
Velocity Triangles, α_1, α_2 , α_3 , β_2 , β_3
C_1, C_2, C_3, V_2, V_3

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

So, the first thing that you need to do is selection of your design point. Now this normally comes from the engine cycle. Engine cycle is the first thing that must have been designed and from which you have a design point selection which tells us at what altitude and what flying condition or what ambient condition taken everything into account the design is supposed to be made. As we have seen before, you may have a design point which is ground static or you may have a design point which is flying, which is typically used for supersonic aircraft engines and in which case the design point would indeed decide the number of starting parameters. Now these starting parameters are given in number two. One of the things you would need to have of course, at the design point is the turbine pressure ratio or pressure drop across the turbine. Then you need to have the mass flow through the turbine which is given as m dot gas and then of course, the maximum diameter that is permissible. This is indeed crucial if you are having to design for a military engine where the maximum diameter is definitely restricted by the size of the aircraft itself. Then of course, the turbine entry temperature t gas are what in cycle analysis one would call t 0 3 or even turbine discussion we have often called it t 0 3 or t 0 1 whichever way you look at it. So, that is T gas.

Now, that gas temperature comes from combustion chamber and you need to have an idea what gas temperature you are letting out into the turbines. So, depending on which stage of turbine you are embarking on, you need to decide the entry temperature to that particular stage of turbine. If it is starting off with a multistage turbine, the first stage entry temperature needs to be decided which of course, is coming from combustion chamber. Now this is something which is normally decided by the state of art of the turbine material, and the turbine cooling technology. As we have discussed in the cooling lectures, this temperature has been pushed upwards are very significantly by the cooling technology from about 1000 k to presently about 18 100 and 19 100 k.

So, turbine entry temperature as written here as t g or t gas, is indeed decided by the state of art of technology of turbine blades. Then of course, the ambient pressure and ambient temperature which is decided by the flight condition or if it is a land based gas turbine it is decided by the ambient condition at which this engine is indeed going to be operated.

Now, this together constitutes the design point. We know very well that the pressure ratio pi 0 t or total temperature (total pressure ratio as we call it) is indeed decided upon after bit of a matching with the compressors.

Now, this matching is something which which is a different you know topic altogether. We have touched upon it a little earlier, but, the more comprehensive part of it is not really inside the scope of this lecture series. Somewhere you know, as you are aware I mentioned should be just touched on a little that you need to match your turbine with your compressor.

So, the matched turbine pressure ratio which also gives a matched compressor pressure ratio needs to be arrived at at the design point. So, you do not decide on a turbine pressure ratio independent of the compressor or the fan. You need to decide upon that after doing a matching exercise.

So, this matching is something which is an independent exercise by itself and one needs to do that. Maybe some other group of people would do that and then pass on the matched value of the turbine pressure ratio to the turbine designer and matched value of the compressor pressure ratio to the compressor designer.

So, that is an exercise which is an independent exercise and needs to be done at this stage before the design is indeed embarked on. So, that pressure ratio comes from an exercise which includes matching of the compressor and turbine or any other load that the turbine is actually catering into. Then of course, you have a number of parameters that you have discussed in great detail in the earlier lectures. One is at the stage loading coefficient, which is normally in most textbooks and as we have mentioned is psi and that is equal to the work done delta h divided by normally half flow u square. In many books, the u is normally the u mean square, but, in many actual applications, people often use U tip square. That means the tip U or the tip blade velocity of the particular turbine rho of course, is the entry density of the gas that is passing through the turbine. delta h of course, is the total work done in terms of total parameters. Now this is the stage loading coefficient which is normally used in most stage characterization and it goes with the flow coefficient phi which is simply C a by U mean. Sometimes in various real applications by various companies, the phi is also mentioned as C a by U tip.

So, instead of U mean many people use U tip as the normalizing parameter both for psi as well as phi. Then of course, as you know, the turbine is typically characterized by the so called psi phi diagram.

We have done that for compressors also if you remember, same thing is done for turbine.

Of course, we can have regular mass flow versus pressure ratio characterization which also we have done in this lecture series. So, the characterization of pressure ratio versus mass flow or the psi phi characterization, both are valid characterizing of working turbines. Both are useful for turbine operation as well as indeed remember a very important issue turbine controls.

So, we need to get the psi and phi values first at the design point. Next thing we need is the degree of reaction. Now if you look at the degree of reaction, again you would have a degree of reaction first at the mean. Then of course, it will vary from the hub to tip. Typically, it would vary quite a lot may not be as much as an axial flow compressors, but, would very still substantially from hub to tip. Then of course, you need to decide what the value of degree of reaction should be. As you know, in case of an impulse turbine, the degree of reaction indeed would be 0; that means, all the static changes occur in stator and no static change occurs in the rotor.

On the other hand, most gas turbines that we are dealing with are reaction turbines. So, they have a positive reaction value which as I mentioned vary from root to the tip of the rotor or the inner diameter to the outer diameter of the annular space of the turbine. The next thing you need to decide is a blade flow turning, first in the rotor and of course, in the stator. Now the rotor of course, gives you the work done.

So, delta b is directly indicative of the amount of work that you can accomplish out of this rotor. Corresponding delta alpha that you get in stator would indicate the amount of turning that is necessary in the stator. That turning of course, is sometimes inevitable or necessary to affect certain amount of change of energy from potential to kinetic.

So, the blade flow turning in rotor for work done in stator for change of energy are vitally important things. Again, these would be variable from root to tip. Now in case of stator, in many designs, it may be constant from root to tip. But, in the rotor, it would vary from root to tip which means the turbine rotors would have some amount of twist.

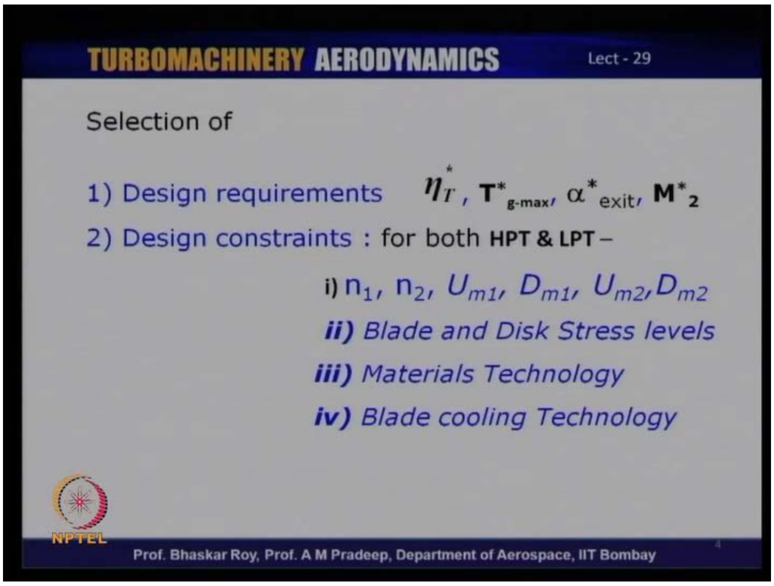
Then you have the velocity triangles of the angles and the velocities alpha 1, alpha 2, alpha 3 and then beta 1 and beta 2 and beta 3 across the rotor corresponding velocity C 1 C 2 C 3 and then the relative velocities V 2 and V 3 across the rotor. This would be first done at the mean. That is where the design needs to be first, you know, initiated. Once you have a design at the mean and you think that this design would hold water and would accomplish the amount of work that you would like to do as mean, as a representative of the entire turbine, then you can sit down and do a variation from root to tip, which means all these parameter that we are talking about indeed would vary from root to tip.

So, variation from root to tip is a separate exercise. We will have a look at that variation in the next lecture in which we deal with the three dimensional blade design.

In today's lecture, we are dealing essentially with the two dimensional aspect of the blade design. So, first we will look at this mean diameter issues. So, that it facilitates or allows us to do a mean diameter design. Indeed in a multistage configuration, all the mean diameters or mean of the blade or design, first of all, the stages stator rotor stator rotor stator rotor of all the stages before any of the stages take up hub to tip a detailed design or the 3D design.

So, the mean diameter design that we are discussing the two dimensional design is indeed the starting of all designs both in case of turbine as we have done earlier in case of compressor. So, this is the way you initiate the turbine design.

(Refer Slide Time: 19:48)



TURBOMACHINERY AERODYNAMICS Lect - 29

Selection of

1) Design requirements η^*_T , $T^*_{g\text{-}max}$, α^*_{exit}, M^*_2

2) Design constraints : for both **HPT & LPT** –

i) n_1, n_2, U_{m1}, D_{m1}, U_{m2}, D_{m2}

ii) Blade and Disk Stress levels

iii) Materials Technology

iv) Blade cooling Technology

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Let us take a look at some of the selection criteria. Now the design requirements are normally put in terms of the turbine efficiency which is decided by the state of art of design. It is decided by the the star represent the design value the T star of the gas. The maximum that can be allowed is decided by the turbine blade technology which includes the cooling technology. The materials science and the metallurgy, all of it put together decide what the turbine entry temperature should be at the design point which is normally one of the highest temperatures.

One would not advocate use of the turbine of this turbine at a temperature much higher than this. Maybe a few degrees higher would be all right, but, substantially higher temperature would be absolutely prohibited once this design temperature has been selected and the design has been made according to the selection. So, turbine entry temperature is the highest temperature in the engine and that is decided after a lot of technology search and then once that is decided at no point of time the engine should work beyond this temperature level.

And then of course, the exit flow angle. Now exit flow angle of turbine is important especially if you have a nozzle as you have in aero engines. The nozzle of course, creates or helps create maximize the thrust that is indeed required for flying of the aircraft.

Now, in the process of creation of thrust what you require is a straight jet which means exit flow angle from the turbine should be 0. The floor should go out straight and go straight into the nozzle and go out straight actually. That is when you have the maximization of your thrust creation. If you create turbine exit flow, which is a whirl inflow that whirl component of the flow is of no use as far as thrust creation is concerned.

So, for thrust creation you need a straight jet; no whirl component. Any whirl component, even a 5 degree 10 degree alpha value at the exit of the turbine would have whirl component which is useless and is a wastage of energy as far as thrust creation is concerned through the nozzle.

So, if you have a nozzle immediately after the turbine that is deployed essentially for creation of thrust, you would be asked to design a turbine where the last turbine exit angle is 0. So, that is a requirement which is often imposed by the engine designer.

Then of course, the Mach number. The Mach number from the turbine exit is important if it is going again into the nozzle. If it is going into the nozzle, (( )) probably going to make the nozzle supersonic or just sonic, which means it may be a convergent nozzle or it may be a convergent divergent nozzle. If it is a convergent nozzle, you were just going sonic. It is important what is the Mach number at which you are starting the nozzle flow, which means, what is the Mach number with which the flow is coming out of the turbine. The other parameter that is important always that cycle designer would have taken care of is a pressure with which the flow is coming out of the turbine.

So, the exit pressure from the turbine and the exit Mach number from the turbine would decide how the nozzle would perform thereafter in an aero engine. If it does not have a nozzle, as let us say, in a turbo shaft engine or in land based gas turbine engines in which case you do not have a nozzle. So, the exhaust energy is not going to be used for creation of thrust or anything. In which case, certain amount of whirl flow may be you know admitted, which means, there is a relaxation on the turbine design. You see the alpha 2 exit or alpha exit at the n puts a restriction on the turbine design or turbine designer.

So, if that restriction is relaxed, maybe you can have a better turbine or a turbine with higher performance. So, these are requirement which are often put on the turbine designer and turbine designer would have to abide by these requirements, in addition to the constraints. Now let us look at the constraints.

Now, the constraints do apply for both high pressure turbine as well as for low pressure turbine. You have constraints on the turbine rotating speeds rpms n 1 and n 2, then that gives rise to the blade speeds U m one which is mean U and mean diameter and then of the HPT and then U mean to a diameter mean of the LPT 2 represents here LPT 1 represent here HPT, and n 1 of course, is a JPT and n 2 is LPT.

So, one here represents HPT two represents LPT. So, the n U and D values need to be decided upon based on the constraints. You may have a stress limit constraint, the compound stress limit which puts a limit on the rotating speed corresponding limit on the blade speed and corresponding limit on the blade size of the diameter of the blade. All of them to put together essentially put a some kind of a constraints on the stresses that come on the turbine which when compounded with the thermal stresses indeed put a huge stress constraint on the turbine blades. This is a constraint that comes from the structure designer of the turbine blades, which is a huge field by itself. Remember there are thermal stresses even in LPT where you do not have cooling.

So, the high temperature and high blade loading creates huge load constraints. Those constraints are passed onto the turbine blade designer in terms of n U and D. He has to abide by these constraints. He cannot go beyond these constraints because those are huge constraints based on turbine loading and those loads put a restriction on the turbine life.

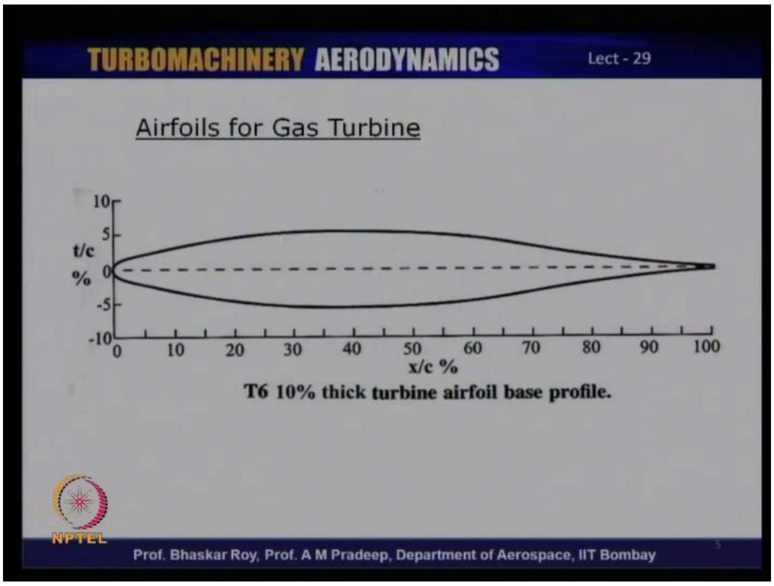
So, the life of the turbine is indeed in jeopardy. So, turbine designer has to abide by these limits. Then you of course, have the blade and the disc stress levels. Now the disc stress level is again a huge problem. Discs like the blades are also made up of high temperature materials. So, even if they are made of high temperature nickel alloys, the stress levels are indeed very stringent.

And there is high temperature all over the place. So, that needs to be factored into the design. The first three parameters n u and d actually come out of the next 3 parameters that we were looking at the blade disc stress levels. The materials technology which is decided by the materials engineer, the material science people and then of course, the blade cooling technology decided by the cooling technologies. We have discussed that in the earlier few lectures. It is a huge field by itself, a fascinating field by itself and they put a few restrictions on the turbine blade designer. You have to abide by those restrictions when you embark on your design.

Having decided or have not discussed, these issues of requirements on one hand, constraints on the other hand, let us start with the blade profiles. What kind of blade profiles are normally used in axial flow turbines?

The most classical airfoil design that is normally used in gas turbines is the T 6 airfoil which is normally used in many of the early gas turbine blades.

(Refer Slide Time: 28:55)



TURBOMACHINERY AERODYNAMICS Lect - 29

Airfoils for Gas Turbine

T6 10% thick turbine airfoil base profile.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Profile that is being shown here is a symmetrical version of the basic blade profile that is normally used in axial flow gas turbines. This profile T 6 profile, there is another one which is famous one. T 1 0 6 which is normally used in low pressure turbine and T 6 is normally used in high pressure turbine.

Now, this profile is a symmetrical profile as you were looking at. This profile is normally bent. The amount of bent that you would like to do is, typically decided by the designer. The same profile may be bent by 90 degree or it may be bent by 100 degree or even by 120 or 130 degree.

So, those decisions are taken by the turbine designer. In the early days of turbine design, this particular profile has been used again and again with various bents. So, the bents or the camber is a separate issue. Quite often you may have a circular arc camber or any other arc camber, may even parabolic arc camber with a total camber of the order of 92 120 130 degrees. We have discussed that in case of turbine that camber is far higher quite often thrice that of a typical compressor camber.

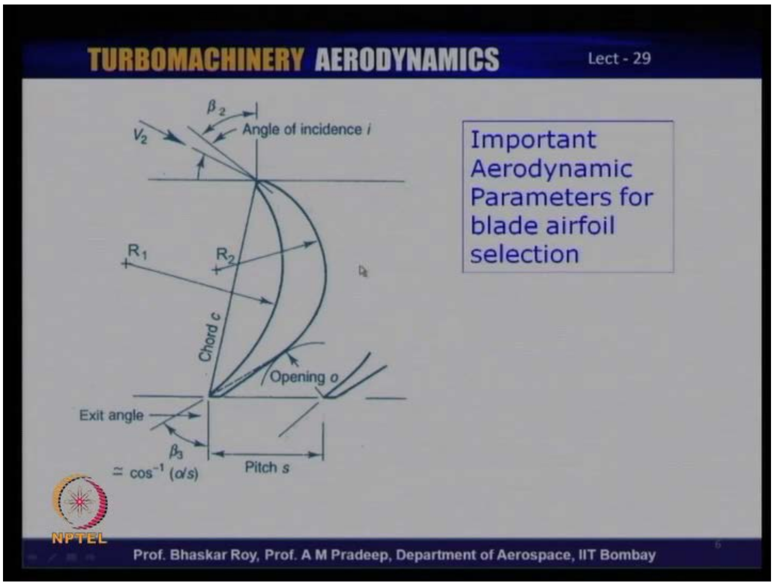
So, that camber on which this blade profile is distributed on. So, this thickness distribution that you are looking at, it is available in many literatures very easily and that thickness distribution is distributed over the camber.

And then, you have a new profile. So, once you distributed over different cambers you have a completely new blade profile. Such a blade profile has been used in many of the turbines in the many of the earlier turbine designs.

As I mentioned, there is another profile called T 1 0 6 which has been used again for many low pressure turbine usages. Of course, we are showing you here which is a 10 percent thick turbine profile. One can have even thicker ones, up to 20 percent which is been used in in rotors. Slightly thinner one here are normally used in stators and thicker ones are actually used in rotors.

Whereas in case of a particular rotor, actually the amount of camber may vary from root to tip. So, you may use the same profile, but, with different camber from root to tip. So, some of those things we will look at in the next lecture. So, this is the basic profile on which many of the early turbines have been actually designed upon. If you have this basic profile, how do you create the particular configuration?

(Refer Slide Time: 31:57)



TURBOMACHINERY AERODYNAMICS

Lect - 29

Important Aerodynamic Parameters for blade airfoil selection

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Now if you look at this diagram, you would need to bend that profile to create this blade or blade section. You would need to conform to the fact that it is coming in with a velocity V 2 let us say this is for a rotor. It is coming in with a certain relative velocity V 2 now. It is set at an angle beta 2 which is what it would feel as the flow is coming in and then you would have to decide on the angle of incidence.

Now, angle of incidence something which we have discussed earlier is typically the angle subtended by the tangent to the camber at the leading edge to the flow direction. So, the flow direction makes an angle of incidence I with the tangent to the camber at the leading edge. So, that tangent to the camber is the angle at which the blade is set and that is beta 2. Now beta 2 is the ideal flow angle with which the flow is supposed to be coming for which the incidence would be 0.

However, most designers often prefer to have a very small angle of incidence often a positive 1 to facilitate that the blade loading is always good blade loading. As you know at a negative angle of incidence, the blade loading indeed would go down.

The next issue is of course, at the exit, where the flow is supposed to be going out with an angle beta 3 which is the exit angle. You would indeed possibly have a very small deviation or flow turning that is slightly different from beta 2 plus beta 3. Now beta 2 plus beta 3 is indeed the flow turning here.

That as we can see could be very high of the order of 100 degrees or so or even more. That needs to be catered to with the shape. In the process, it is entirely possible that and we shall see that the flow may not stick to right up to the trailing edge. There may be very small deviation much less than what we have seen in case of compressors and quite often it is a very small amount.

Then of course, you have to decide fundamental airfoil parameters. The chord of the airfoil which is absolute value of the chord is decided by a number of considerations indeed what should be the surface area of this surface and surface area of this to allow for sufficient contact between the blade surface and the gas which is passing through. That contact as you know of course, transfers the energy from the gas to the blade.

So, there has to be a sufficient contact on the surface between the gas and the solid body of the blade for effecting the work transfer. So, that is an absolute amount that has to be decided by the designer what should be the chord because that chord will decide the surface area of contact between the blade and the gas. This is decided by a lot of calculations of the energy that is to be transferred.

Now, once you have decided on the chord and you have some idea what beta 2 plus beta 3; that means the blade camber. You need to decide on the two surfaces. You have a radius of curvature of one surface and then you have a radius of curvature of the other surface. That means both the surfaces; the pressure surface and the suction surface are indeed actually circular arcs.

Many modern designers as we shall see later on do are not necessarily stick to the circular arcs. They often devise different curvatures not necessarily circular. These blades in the classical design, the circular arc is followed by normally a straight line on both the surfaces and then a little rounding at the trailing edge and then rounded at the leading edge.

In many of the modern design, the rounding at the leading edge is very prominent or very large essentially to cater to the cooling technology to be embedded inside it. So, many of the modern designs, accommodate a very large rounded leading edge as we have seen in the last lecture on blade cooling. That incorporates or has embedded cooling technology inside that rounded leading edge. Now, rounded leading edge aero dynamically is actually a compromise.

It is a sacrifice because more the rounded leading edge; that means, more the leading edge radius more would be the basic aerodynamic penalty in terms of profile loss of the airfoil. This is known. This is very well known.

So, the aerodynamicist often does a little bit of sacrifice in the aerodynamic penalty or loss to accommodate blade cooling technology inside the blade. This is typically necessary for high pressure turbine HPT plates because you need cooling there.

So, many of the HPT blades would have much more rounded leading edge whereas, the LPTs may not have that rounded leading edge because quite often LPT or the last few turbines specially do not have any cooling technology embedded inside.

And then of course, you need to decide on the opening or more specifically the throat of the turbine passage. Now, the flow coming through this passage typically would have a converging curve passage and it would indeed have the minimum area over here at this opening which is often the throat of the passage.

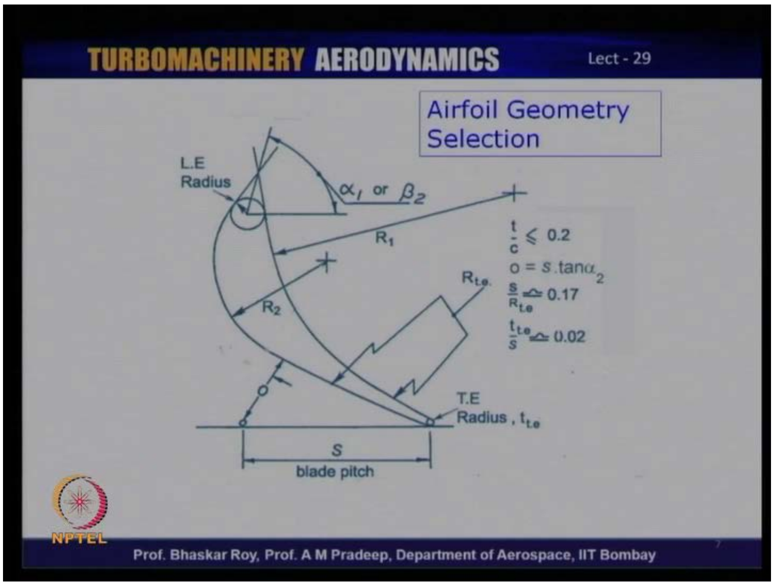
Now, throat of the passage is of course, the constriction or the restrictions on which the blades are deliberately designed to create an expanding flow or an accelerating flow over this blade profile. Now what happens is this opening is decided by also the pitch.

We shall discuss how to decide on the pitch again later on. More spacing you provide; that means, more apart the blades are you have a lesser and lesser surface friction related losses. On the other hand, more closer they are in terms of spacing you would actually have more and more surface friction losses. But, you are going to have more and more turbine work transfer.

So, more apart they are normally, the losses are less. Primary losses, the surface friction losses, less closely they are packed more you have the losses. But, you have better presumably and definitely calculable better performance features.

So, it is a slight you know tug of war or a compromise between more work that can be accomplished probably with efficiency penalty. In other case, where you have higher efficiency probably you are going to get less work done. So, this compromise is what the designer would have to decide upon early on during the design process. So, these are the basic flow parameters and then we start off with the geometrical parameters.

(Refer Slide Time: 40:03)


TURBOMACHINERY AERODYNAMICS Lect - 29

Airfoil Geometry Selection

$\frac{t}{c} \leqslant 0.2$

$o = s.\tan\alpha_2$

$\frac{s}{R_{t.e}} \simeq 0.17$

$\frac{t_{t.e}}{s} \simeq 0.02$

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

If we carry on with the geometric parameters, we see that this is the stator. The earlier one we were looking at was a rotor. Now this is the stator where your entry angle is typically given in terms of alpha. Typically, you are likely to have a rounded leading edge. This is what I was talking about that you have more rounded leading edge for typical stator because a stator is likely to be cooled. Even some of the early LPT stator may be cooled. Rotors may not be cooled. HPT of course, rotor and stator both are cool.

Now, you can see here that the radius of curvature that you give to a typical stator blade it is circular around this area. Whereas, it is unlikely to be a circular all over. So, you have a circular arc starting early on, maybe very close near the leading edge. Then you have a circular arc and then from here onwards, you probably have a straight line, more or less straight line over here.

So, you have a circular arc over here and then you have another circular arc over here. This is the radius of curvature or radius of the circular arc. This is the radius of this circular arc and typically they end up with straight lines over here. Then, at trailing edge rounding, typically given in terms of trailing edge radius. So, you have a number of geometrical parameters to be decided upon. Now this throat area is very important for stator design because in many stators, that throat is likely to provide sonic flow and that is related to the blade pitch that you are getting. Of course, if the pitch is more throat is going to open up.

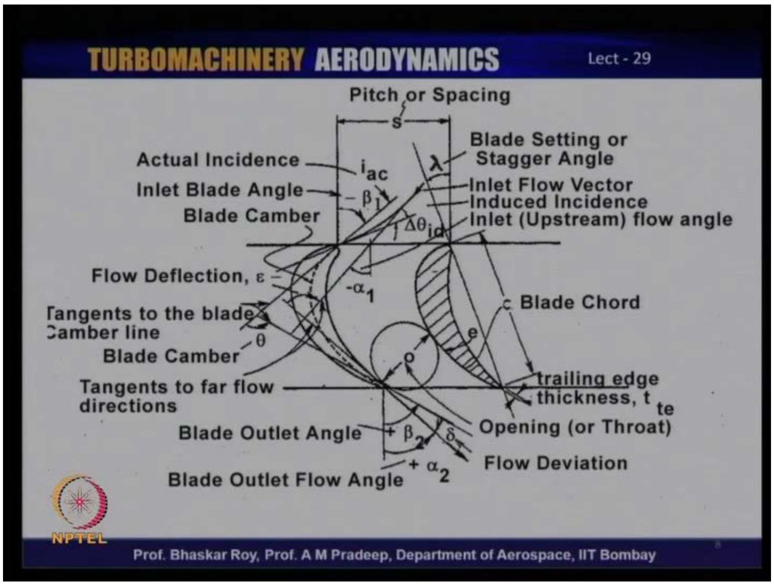
So, it is given here in terms of o is equal to s into tan alpha 2. alpha 2 is angle with which the flow is indeed coming out. This is decided often by now if you have 90 degree over here, it means that the flow will actually be not tan alpha but it will be sin alpha. If this angle is 90 degree then of course, o is s tan alpha.

So, depends on whether by design this angle is 90 degree or this angle is 90 degree. Many designers would like to have this as 90 degree because this is a straight line. Some would like to have this as 90 degree. Of course, this is always a straight line.

So, it depends on the designer and depending on that, o is the throat area is decided upon. Then, of course, the t by c, the ratio, the the thickness which is decided. We saw the t by c ratio of the t 6 blade which was 10 percent here we see it is given as 20 percent.

Then, of course, the various other parameters such as the spacing to radius of the trailing edge and then spacing to trailing edge radius which is given as 0 2. Some of these ratios in terms of trailing edge radius, in terms of the chord or the geometrical parameters that the turbine designer would have to finally carry out before it is given for analysis and then later on for fabrication. So, these are the geometric modelling issues that the turbine designer would have to decide up on.

(Refer Slide Time: 43:50)



TURBOMACHINERY AERODYNAMICS

Lect - 29

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

This is a picture that tries to capture everything that the turbine indeed has. You have to begin with, which are decided upon the throat area which is typically done by actually drawing a circle over here. Then of course, the inlet flow angle coming in beta 1, exit flow angle beta 2 as I mentioned, you can have a small deviation flow. Deviation over here which means the floor does not quite actually cater to either beta 2 or alpha 2 which would be in case of a stator. Then of course, depending on the chord you decide upon the blade stagger angle. So, this is your blade chord and that is your blade stagger angle angle it makes with the axial direction.

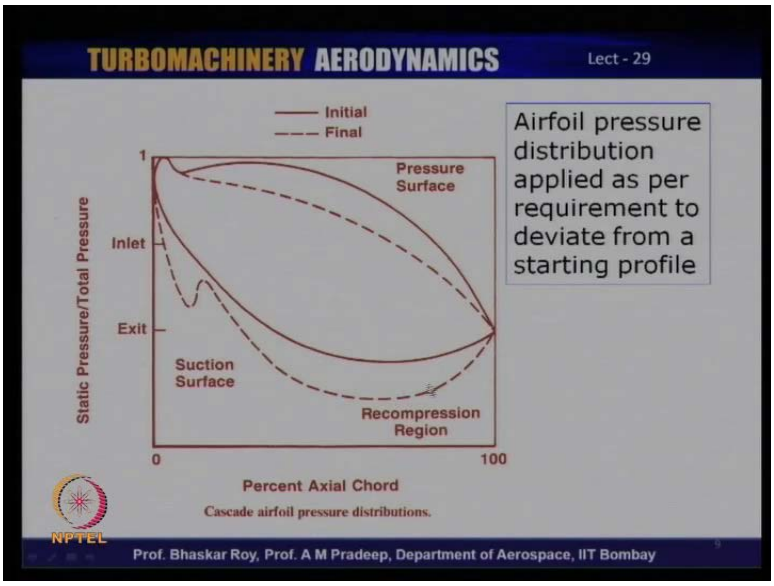
So, that is your blade stagger or blade setting or blade fixing angle as the assembly people would call it. So, you would need to decide on those things. As you can see here, the blade stagger angle really speaking has nothing much to do with the aerodynamics of the flow. It is really necessary for blade fixing and setting of the blade. Because, the huge camber that turbine design blades normally carried by design actually sets it apart from the chord direction of the chord. As a result of which, it is really nothing to do with the blade setting angle. But, at the end of the day you have to provide the blade setting angle by design because the blade will be actually fix there at the time of assembly.

Then of course, this is your flow deflection beta 1 by minus beta plus beta 2 or alpha 1 plus alpha 2. Then of course, these are the tangents to the camber line. So, this is one tangent, this is another tangent and the angle between the two is the blade camber.

So, blade cambers are decided by the tangent to the camber line at the leading edge and at the trailing edge. Incidence is decided by the flow direction with the tangent to the chamber at the leading edge. The deviation is decided by the flow direction with the tangent to the camber at the trailing edge.

So, all those things geometrical as well as flow parameter of fluid dynamic gas dynamic parameters are put together in this diagram. It captures almost everything that is necessary for the turbine designer to decide upon. All these parameters would have to be decided by design. None of it can be left out. All these parameters would need to be decided upon by design.

(Refer Slide Time: 46:47)


TURBOMACHINERY AERODYNAMICS

Lect - 29

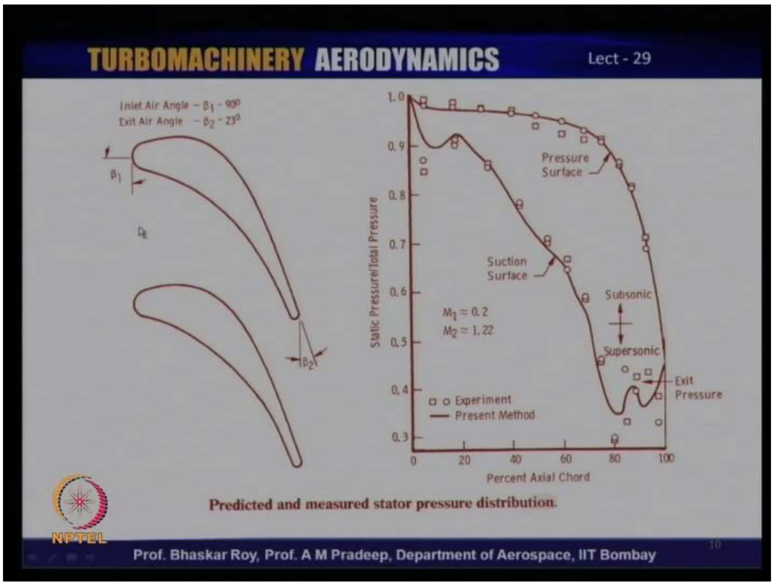
Airfoil pressure distribution applied as per requirement to deviate from a starting profile

Cascade airfoil pressure distributions.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Now, this is what the turbine designer would be looking at. You have the pressure surface cp distribution and one is the ideal one which you start off with. Then of course, you make small changes in the modern design. You make the changes with the help of CFD and you may get final cp distribution which is something like this. What I show here is static pressure by total pressure similar to cp and it shows that it does not follow a smooth curve than a small thing over here. Then there is small prominent recompression; that means, a small diffusion of the flow before it hits the trailing edge of the suction surface. So, this is done deliberately to deviate from the ideal starting profile to arrive at a final profile.

(Refer Slide Time: 47:46)



TURBOMACHINERY AERODYNAMICS Lect - 29

Predicted and measured stator pressure distribution.

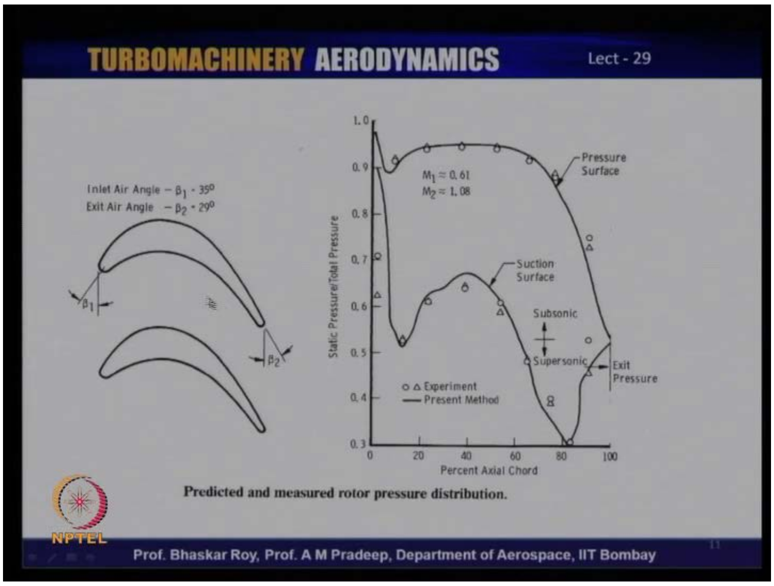
Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

This is what is at typically done for a stator. Typically profile needs to be decided or designed in a cascade form. He does not decide an airfoil form. It is in a cascade form with all those spacing and other parameters in place. Only then you know the cp distribution. The cp in cascade is quite different from the cp in actual single airfoil.

So, you need to have the cascade static pressure to total pressure distribution decided upon. This is your pressure surface and this is your suction surface and at the exit you may have some slight things over here and finally, of course, they have to match.

In this particular case for example, we see that the exit Mach number here could be as high as 1.2 to 2 which means it is going out supersonically. Its going out entry is .2. So, it has accelerated from M 1 2 to M 2 1 to 2.2. A huge acceleration has taken place over this blade passage and as you can say there is a huge convergence of the blade passage which gives rise to these huge expansion or acceleration.

(Refer Slide Time: 49:09)



TURBOMACHINERY AERODYNAMICS

Lect - 29

Predicted and measured rotor pressure distribution.

NPTEL

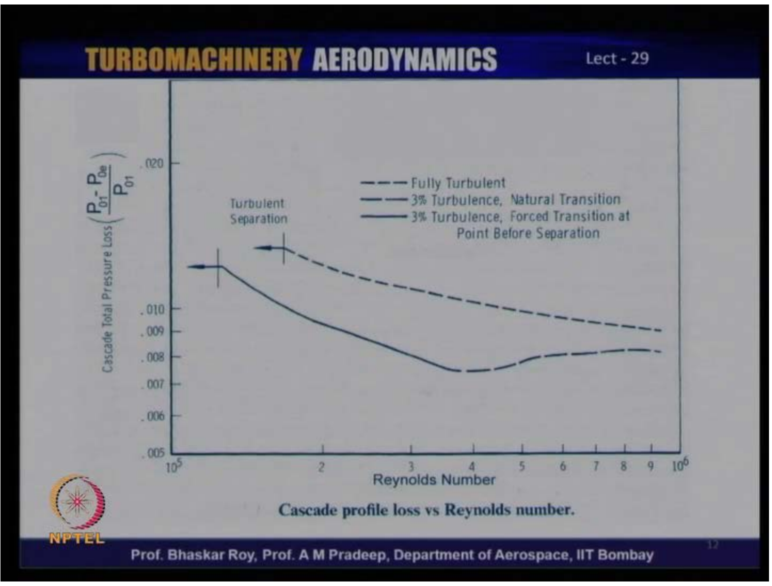
Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

This is a picture of a rotor where as you can well imagine, the acceleration is not as much as in the stator. The flow comes in with a Mach number relative Mach number .61. Part goes out with a Mach number which may be slightly or marginally supersonic.

It comes in with an angle of 35 goes on with an angle 29. So, beta 1 plus beta 2 would be the turning angle and the turning angle that is shown here is not necessarily very high. You can have rotors that have turning angles even higher than that. But, in gas turbines as we have discussed before in quite a detail that the turbine rotor design does not depend entirely on the turning, it depends also on the reaction. So, acceleration that is taking place would give you the reaction which will give you the additional work that is accomplished by this particular rotor. One can see that finally, experiments have been done in cascade tunnel to match the experimental values with the design values.

So, that you are assure that you have a reasonable matching between what you have design and what you are likely to accomplish in actual blades.

(Refer Slide Time: 50:27)



TURBOMACHINERY AERODYNAMICS

Lect - 29

Cascade profile loss vs Reynolds number.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

T

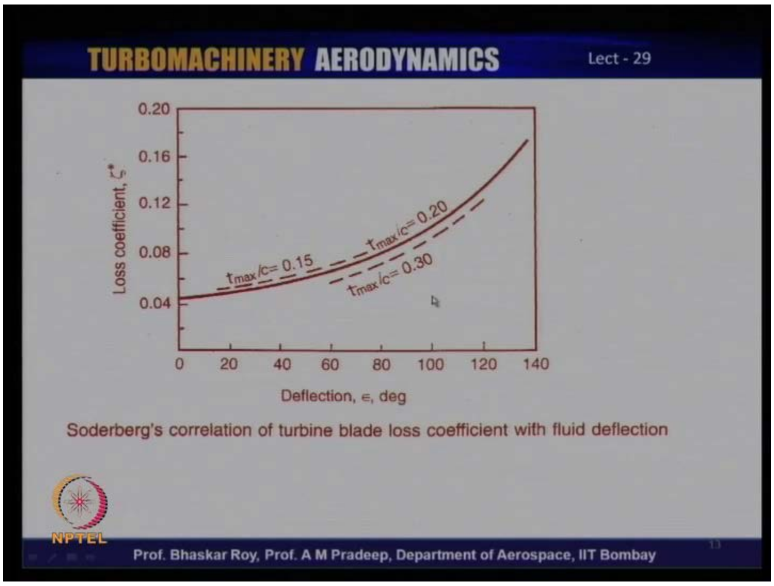
This is what happens when you have turbine blade. What is shown here is the pressure loss. You remember pressure loss is what gives rise to the efficiency penalty and as you can see here if the flow is turbulent; the efficiency penalty is like to be higher.

So, once the flow actually becomes turbulent as we have seen, the flow becomes turbulent somewhere on the blade surface. As the local Reynolds number goes up and typically the Reynolds number above 2 tends to have 2 to the power 2 into 10 to the power 6. It typically has a tendency to become turbulent flow and then of course, you know it has a turbulent flow characteristic and necessarily the loss is going to be higher.

So, turbulent flow has a higher loss characteristic which is frictional loss is basically what normally you gain in terms of weight loss. Then of course, the 3 percent turbulent which is after the natural transition and then this is what happens if you have a 3 percent turbulent which is force transition by some method of tripping, the transition has been forced and as a result of which you can see the losses can be reduced.

So, if you have a tripped flow by some means you can reduce the losses and as a result of which you can have lower losses. Whereas, if the flow is turbulent right in the beginning, the losses are going to be very high. Now, in axial gas turbines, in turbines quite often the turbulence level is quite high. It is quite often seen that the turbulence levels are indeed of the order of 3 percent or even higher.

(Refer Slide Time: 52:18)



TURBOMACHINERY AERODYNAMICS

Lect - 29

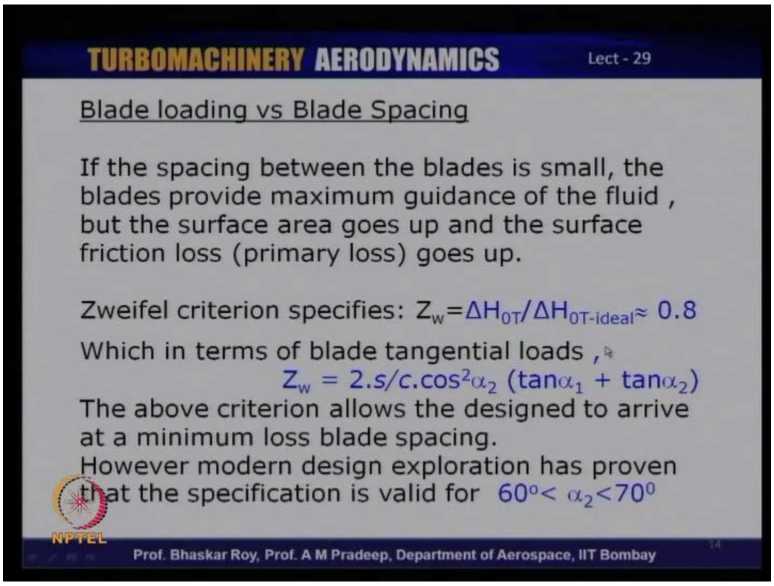
Soderberg's correlation of turbine blade loss coefficient with fluid deflection

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

This is the loss coefficient in terms of a certain correlation created by a gentleman called Soderberg. This gives the loss coefficient with the deflection of the flow. As you can well imagine, as the deflection of the flow that is beta 1 plus beta 2 or alpha 1 plus alpha 2 increases at a certain point of time, the loss would indeed start increasing. These are given in terms of t by c of the blade 15 percent, 20 percent and 30 percent. As you can see, the initial losses were very high, but, you can have losses that are little lower if you have control over the blade profile.

So, losses typically would go up if the deflection attempted is very high. You have to decide what kind of deflection would be appropriate for your design. Knowing that at some point of time you would have to pay a bit of loss penalty.

(Refer Slide Time: 53:28)



TURBOMACHINERY AERODYNAMICS Lect - 29

Blade loading vs Blade Spacing

If the spacing between the blades is small, the blades provide maximum guidance of the fluid , but the surface area goes up and the surface friction loss (primary loss) goes up.

Zweifel criterion specifies: $Z_w=\Delta H_{0T}/\Delta H_{0T\text{-ideal}} \approx 0.8$

Which in terms of blade tangential loads ,

$$Z_w = 2.s/c.\cos^2\alpha_2\ (\tan\alpha_1 + \tan\alpha_2)$$

The above criterion allows the designed to arrive at a minimum loss blade spacing.

However modern design exploration has proven that the specification is valid for $60^o < \alpha_2 < 70^0$

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

14

Then of course, we come to a very important issue called blade loading. This is to be factored in with blade spacing. This is typically decided because as I mentioned earlier, if you pack the blades more you get a better guidance of the flow through the curvilinear passage. But, your friction losses are high. As a result friction loss is a primary loss and as a result your efficiency penalty would go up.

On the other hand, if you pack the blades space the blade apart your guidance would be a little less, but, your losses would be going down and your efficiency would be higher. So, Zweifel decided way back in 1945 that value of .8 is a reasonable compromise between guidance of the flow and the penalty that you pay in friction loss.

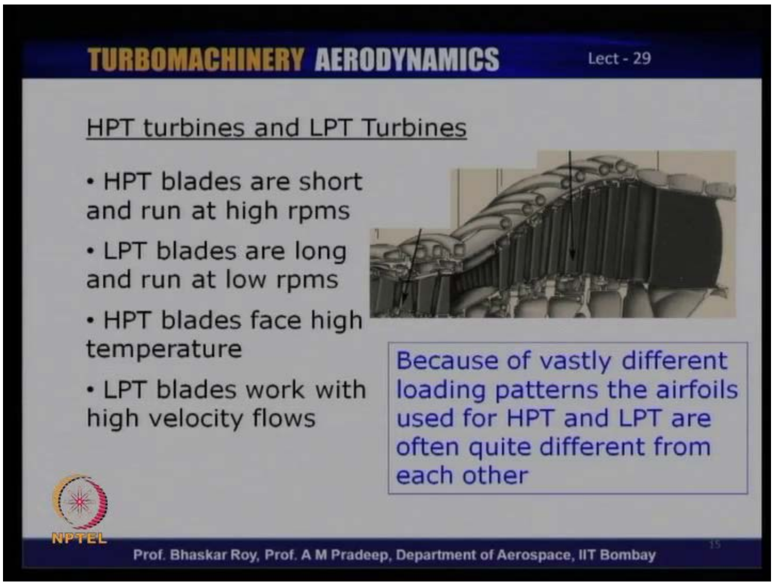
As a result of which, Zweifel criteria have been used in turbine design for many years. In terms of blade tangential loading can be written down in terms of Z W which is a Zweifel parameter as in terms of twice by s by c spacing by chord into cos per alpha 2 into tan alpha 1 plus tan alpha 2.

Now, this allows you to select the value of spacing. So, one can find out or calculate the spacing from the Zweifel criterion and then decide the number of blades that you should have. However later, designers have explored more and have found that this Zweifel criteria is very good if your exit flow angle is between 60 and 70 which indeed is actually a very popular exit angle design zone.

However, if your exit angle is less than 60 or more than 70 by design, you probably need to think a little before you apply this Zweifel criterion because this Zweifel criterion may not be valid.

So, Zweifel criterion is indeed valid for alpha 2 between 60 and 70 which is the more popular alpha 2 design zone. But, if by chance it is beyond this range, then Zweifel criterion remember may not be valid. So, you may not use the value .8 you may like to use some other value to decided separately.

(Refer Slide Time: 55:59)



TURBOMACHINERY AERODYNAMICS Lect - 29

HPT turbines and LPT Turbines

- HPT blades are short and run at high rpms
- LPT blades are long and run at low rpms
- HPT blades face high temperature
- LPT blades work with high velocity flows

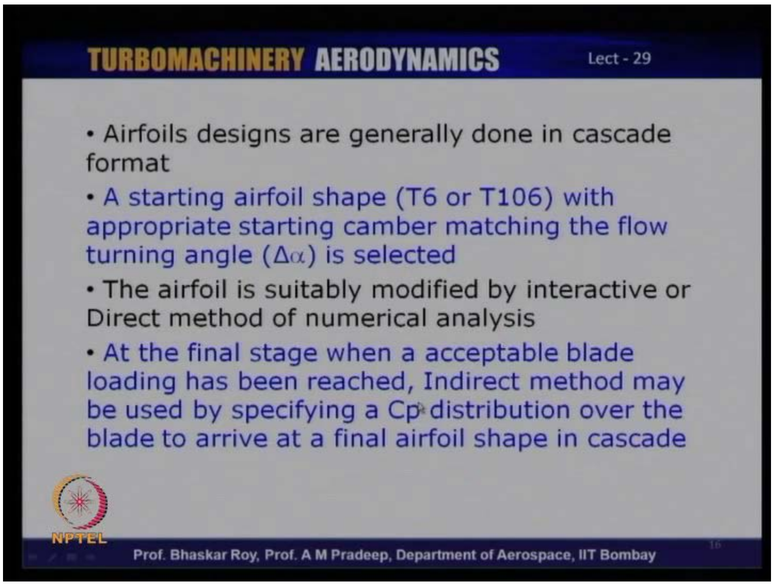
Because of vastly different loading patterns the airfoils used for HPT and LPT are often quite different from each other

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

HTP turbine and LPT turbines the difference between the two needs to be very quickly pointed out. HTP blades are short and they run at high rpms. LPT blades are long. As you can see, they are 3 4 times longer than HPT blades. On the other hand, they will run at low rpms. HPT blades face very high temperature coming from the combustion chamber. LPT blades work with very high flow velocities because through the HPTs the flow velocity has gone up.

So, the average flow velocity here is likely to be of a higher order. Because of these differences the airfoils used for HPT and LPT are quite different from each other. As we have seen very early on they had decided that t 6 profile is good for hpts and T 1 0 6 is most likely to be used for LPTs. So, but, the modern designers of course, have different approach. They do not use those profiles very strictly any more.

(Refer Slide Time: 57:10)



TURBOMACHINERY AERODYNAMICS

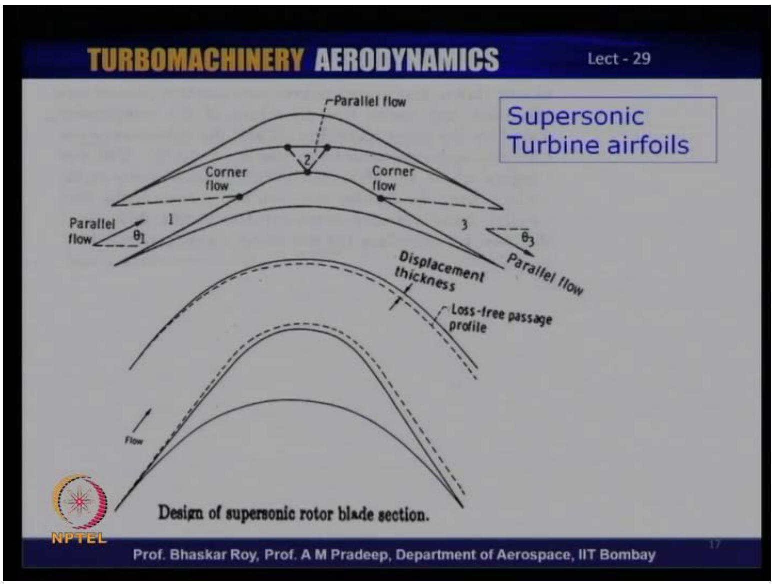
Lect - 29

- Airfoils designs are generally done in cascade format
- A starting airfoil shape (T6 or T106) with appropriate starting camber matching the flow turning angle ($\Delta\alpha$) is selected
- The airfoil is suitably modified by interactive or Direct method of numerical analysis
- At the final stage when a acceptable blade loading has been reached, Indirect method may be used by specifying a Cp distribution over the blade to arrive at a final airfoil shape in cascade

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

So, the modern design starts off with an aerofoil shape T 6 or T 1 0 6 and then it is modified by CFD certain interactive or direct method of numerical analysis. So that means, you feed this airfoil try to find out its aerodynamic performance and then see whether it is good for you or you change the profile again and feed it into the analysis which is what most people do. However, there is a indirect method which is normally adopted towards the end of the design. When you have a reasonable idea of what would be the cp distribution over the blade by the earlier method off iterative or interactive method and then you feed that final wanted or desired cp distribution and adopt an indirect method of creating your blade profile. In which case, the blade loading is already decided upon and then you get the final profile decided upon from the indirect method of CFD analysis.

(Refer Slide Time: 58:21)



TURBOMACHINERY AERODYNAMICS

Lect - 29

Supersonic Turbine airfoils

Design of supersonic rotor blade section.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

17

Here we see finally, look at supersonic turbine blade profile. Now supersonic blades are as you can see they are sharp because they have to negotiate flow that is coming in with supersonic Mach number.

So, the blades would have to have sharp leading edges. There is no scope for rounded leading edges here which means you cannot have cooling in these blades. So, typically supersonic blades like these would have supersonic flow through the entire blade passage. It is coming in supersonically and going out supersonically. Inside of the passage it would have continuous strain of shocks or fans.

It is most likely that the flow would be going through the entire blade supersonically. One of the oldest methods of designing supersonic turbine blades is not to have any acceleration or deceleration inside the passage, but, a constant supersonic Mach number blade. That was the earliest design that people have used for supersonic turbines.

The supersonic turbine blades also are configured using the method just was discussed in the last slide. So, there is a certain amount of difference between what you can have and then if you accommodate the boundary layer and the losses that can occur. So, very slight difference in the flow profiling may need to be done with the help of modern CFD methods to get your final blade profile. It would still have a sharp leading edge and a sharp trailing edge. Typically such blades have been used in rocket motors. Those blades would indeed have very high temperatures, but, they are likely to be made of ceramics or refractory materials that do not need cooling. As a result of which you can do without the cooling methodology. You can simply make the blades out of very tough material like ceramics which can withstand very high temperature and for a certain period of time specially used in rockets or missiles which may need to be used for only few hours. Then they are appropriate and then of course, as we know, if you deploy supersonic airfoils in supersonic turbines, the amount of work done would be hugely more. You can get very large pressure ratio across such supersonic turbines.

So, supersonic turbines are very special things normally not used in commercial gas turbines either line based or aero engines. They are used in very special cases as I mentioned one of the possibilities is in rockets or missiles where you have small turbine machines for turbo pumps.

So, that brings us to the end of fundamental profile discussion on various kinds of profile that are used in axial flow turbines. In the next class, we will be discussing how to use these profiles and what is the method by which you finally create a three dimensional blade from root to the tip of a blade. 3D turbine blade design is what we will be doing in the next lecture.