Turbomachinery Aerodynamics

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Lecture No. # 26

Tutorial – 4: 3D Flows in Axial Flow Turbines

We are talking about axial flow turbines, and in last class, last lecture, we talked about how to design and bring into the design steps and design features, three dimensionality of flow through axial flow turbines. Now, we know that the flow through the axial flow turbines, as in axial flow compressors, is normally annulus in nature and that flow through the annulus space that is available to the turbines is often not exactly uniform.

So, some aspect of the non uniformity or some aspect of the variation from the lower radius to the outer radius or inner radius to the outer radius, and more specifically from the root to the tip of the blade of a rotor needs to be factored into to begin within the design, and later on, in the computations, and of course, later on in the analysis. We have seen how some of these things can be brought into simple analysis. That we had done in the last class without getting into more complex computational analysis.

As I mentioned, we shall do computational, an introduction to computational analysis through turbo machines towards the end of this lecture series, but right now, we are looking at turbines specific certain theories which factor in the three dimensionality of the flow and built it into the design. So, most of it is indeed used for design, and then, immediate pose design analysis to find out how the turbine is actually going to behave.

So, in today's lecture, we will look at some problems that actually use these theories that we have done in the last class, and then, try to actually solve some problems which are prescribed problems, and from the problem statement, we tried to figure out what kind of solutions can be arrived at using the theories that we have done in the last lecture.

And towards the end, I will leave you with a few problems to solve by yourselves so that you can get the feel of the application of these theories to actual problems, realistic problems and you also get a feel of the numbers. It is essential for an engineer to get the feel of the numbers and that is why it is essential that we look at a few problems which are probably a little textbook problems, simplicity problems where, you know, typically you have all the data you require. In a real life problem, you often may not actually have all the data that is require to solve, but we are dealing with problems where the problem statement gives you all the data that you require.

And now, you need to use the theories that we have done to arrive at solutions, and in a process, one learn how the solutions would look like and indeed as I said you get a feel of the numbers. What the numbers would look like? So, that is very important for all practical engineers. So, let us look at some of the problems related to three-dimensional flow in axial flow turbines. Now, in axial flow turbines, that we are going to do some solved problems, and then, I leave you with some exercise problems to solve for yourselves.

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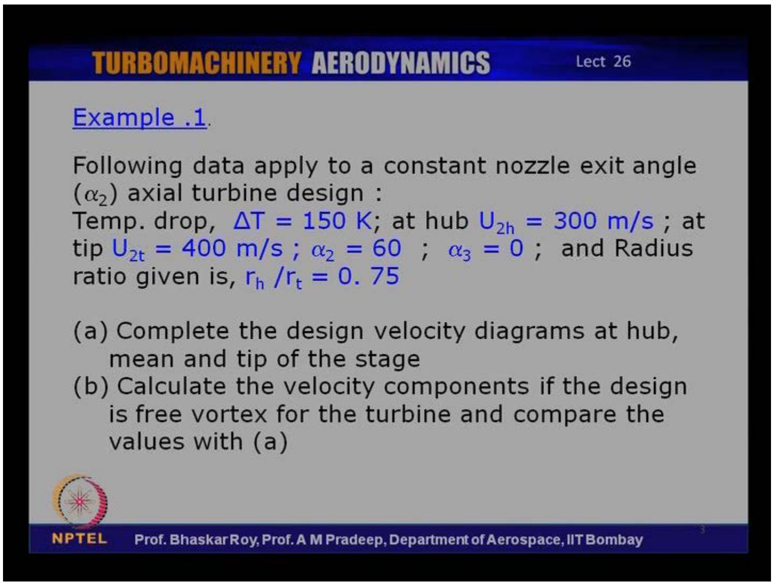

Now, in the solved problems, we will first look at the problem statement. In the first problem, the problem statement shows that a constant nozzle exit angle which we have designated earlier is alpha 2 is being use for axial flow turbine design. In which, it is prescribed that the temperature drop should be 150 k, and at the hub, the flare velocity a blade speed u is 300 meters per second, and at the tip, it is 400 meters per second.

At it is prescribed that alpha 2 is 60 which is constant as prescribed from a root to the tip hub to the tip and alpha 3 is 0, that is, 0 whirl at the exit of the rotor. The radius ratio given for this particular problem statement is 0.75, that is, hub radius to tip radius ratio is 0.75that is prescribed here. The problem asks a solution in which he should complete the design velocity diagrams at hub mean and tip of the stage, and thereafter, calculate the velocity components if the design is a free vortex design for the turbine and compare the results of that with that of constant nozzle exit angle. So, one can look at the whole thing from a free vortex point of view and compare the results. So, this is a problem statement which we can now try to find a solution to.

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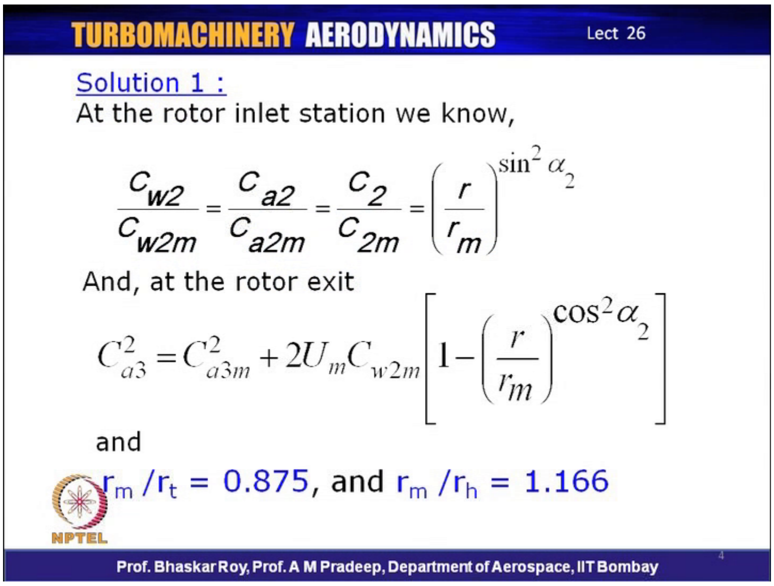

Now, at the rotor illustration, we have done in the last class - the equation for variation of whirl component is defined by the variation of alpha 2 and that is given by C W 2 by C W m which is the mean and that is also equal to C a 2 by C a 2 mean, which is also equal to C 2 by C 2 m which is mean and all these velocity ratios are equal to radius ratio r by r mean r being at any radius to the power sine square alpha 2. Now, this is what we had done in the last lecture following which, what we get is, at the rotor exit, the actual velocity C a 3 square is equal to C a 3 mean square plus twice U m into C W twice m whole thing multiplied by 1 minus radius ratio r by r m to the power cost square alpha 2.

Now, this is also the theory that we had the expression; we had shown in the last lecture. Now, from the prescribed radius ratio that is given, we can see that the mean to tip radius ratio would be 0.875 and mean to hub radius ratio would be 1.166, that is calculated from the hub to tip radius ratio that is prescribed in the problem statement.

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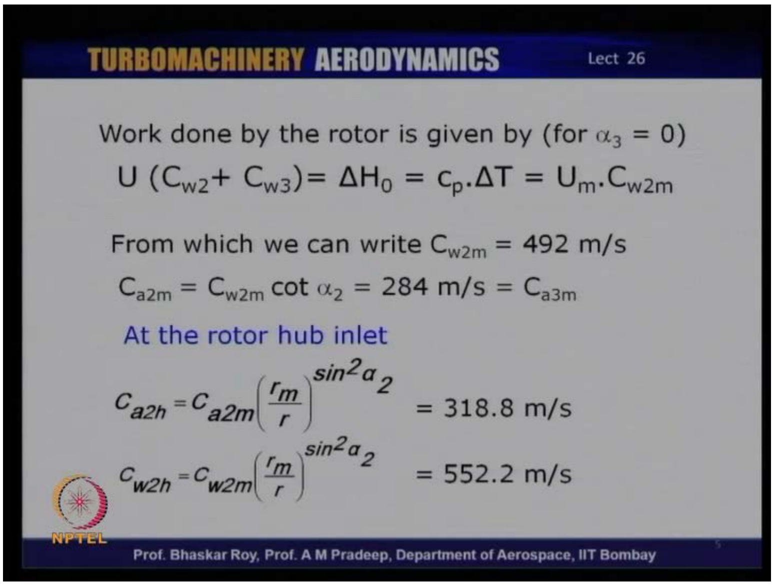

Now, the work done by the rotor is given by the rulers equation which you are all aware of. Now, in this particular problem statement, alpha 3 would be equal to 0; exit whirl component is 0, which means C W 3 indeed would be 0, and in which case, the specific enthalpy rise or, you know, specific work that we normally use for aero thermodynamic relations, that is, a c p into delta t would be equal to U m into C W 2 m C W 3 being 0, and from which, we can write that C W 2 m would indeed be 492 meters per second and corresponding C a 2 would be from the velocity triangles that you can draw at station 2 that is before the rotor and that would come out to be 284 meters per second. As per the prescription, that also would be equal to a actual velocity at the exit of the rotors C a 3 m.

Now, at the rotor hub, at the inlet of the rotor, one can write a axial velocity C a 2 h is equal to C a 2 m to the multiplied by a radius ratio r m by r to the power sin square alpha 2 and this would yield a axial velocity of 318.8 meters per second. On the other hand, the whirl component at hub, at the inlet C W 2 h would be a C W 2 m into r m by r to the power sine square alpha 2 and that would be 552.2 meters per second. So, you now start getting the components of the velocities at station 2, that is, before the rotor at the rotor inlet.

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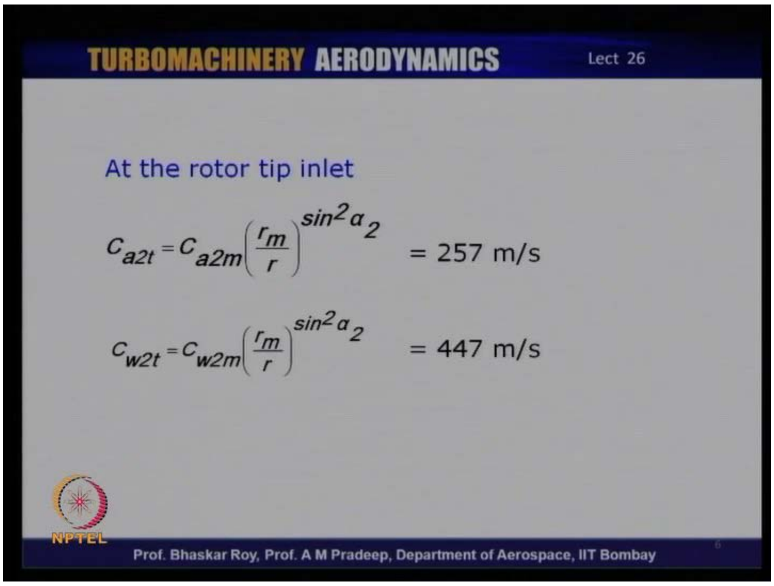

Now, at the rotor tip of the inlet, one can now find the actual velocity using the same relation, that is, C a 2 m into r m by r to the power sin square alpha 2, and in which case, the actual velocity would now be 257 meters per second, and at the whirl component, C W 2 tip would be 447 meters per second. So, as one can see that the whirl components has actually decreased from hub to the tip, whereas, the actual velocity is also decreased a little from hub to the tip and this is a consequence of the fact that alpha 2 has been held constant from root to the tip of this prescribed problem. Soon as a result of which, we now have all the velocity components that are required at the inlet to the rotor.

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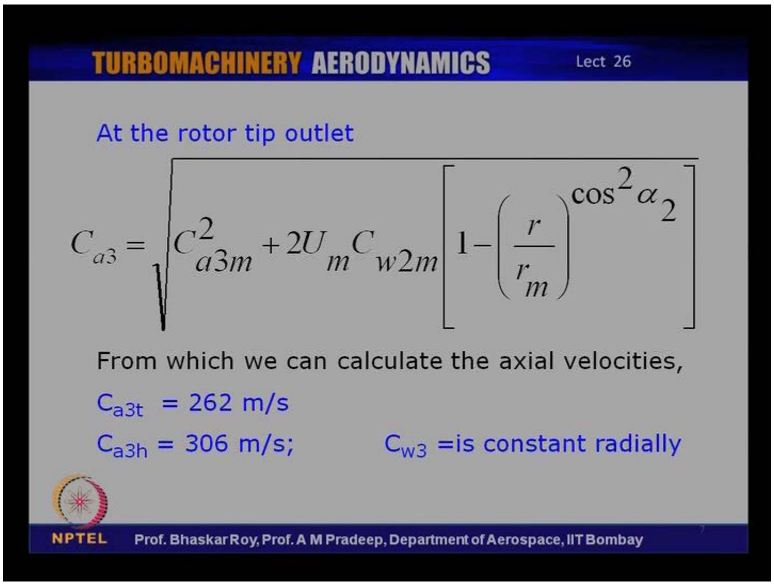

Now, at the rotor tip outlet, we can find what the actual velocity would be and this can be found from the axial velocity relation that we had done earlier and that is given by C a 3 equal to whole thing root over C a 3 square plus twice U m C W 2 m multiplied by 1 minus radius ratio r by r m to the power cos square alpha 2, and if you do that, we can calculate the actual velocities at tip and hub as at the outlet as 262 and 306 meters per second.

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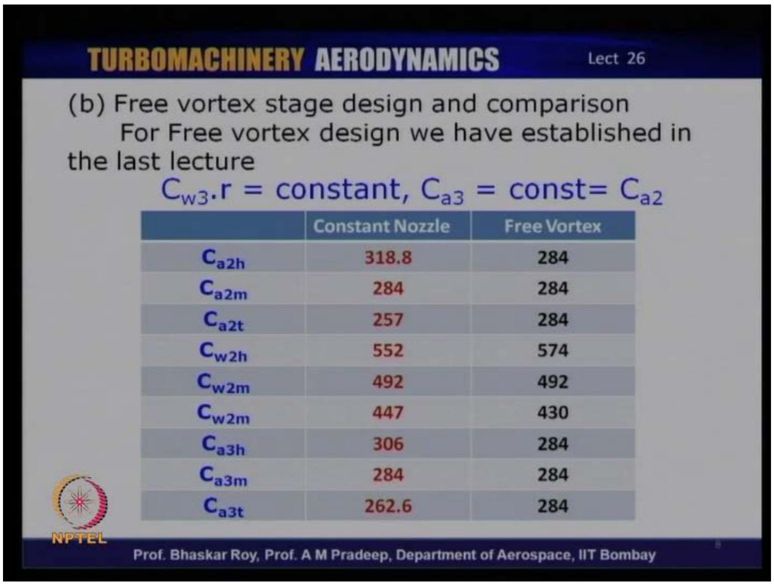

So, once you apply the relations that we had done in the last class for three-dimensional flow estimation, we now have the axial velocities at tip and hub at the outlet to the rotor. On the other hand, if we calculate all the values with reference to the free vortex design, we can see that the velocities that we get in comparison to the nozzle angle can be now written down in a tabular form, and one can see that these values are the ones in constant nozzle angle are given in red and the free vortex values are given in black, and the actual velocities as you can see in, in, front of the rotor and behind the rotor are constant for free vortex, only the whirl component is changing as per free vortex variation from tip to hub. On the other hand, for constant nozzle angle as one can see all the velocities are varying, and essentially only at the mean, the values of free vortex and the constant nozzle angle are same at the tip as well as at the mean, the axial velocity the whirl component velocity and the exit axial velocity they are all same at the mean, but at the hub and the tip, the constant nozzle angle gives completely different values compared to that of free vortex.

Now, this is something which you may like to take a look at and you may like to sit down and draw all the velocity triangles that are born out of this two calculations, two sets of design calculations and you will probably find that you get completely different blade shapes. The blade shapes that come out of this two design exercises would indeed be quite different from each other and that would tell you that, if you use different kind of design law or design philosophy, you would in end up getting quite different blade shapes, the three-dimensional blade shapes.

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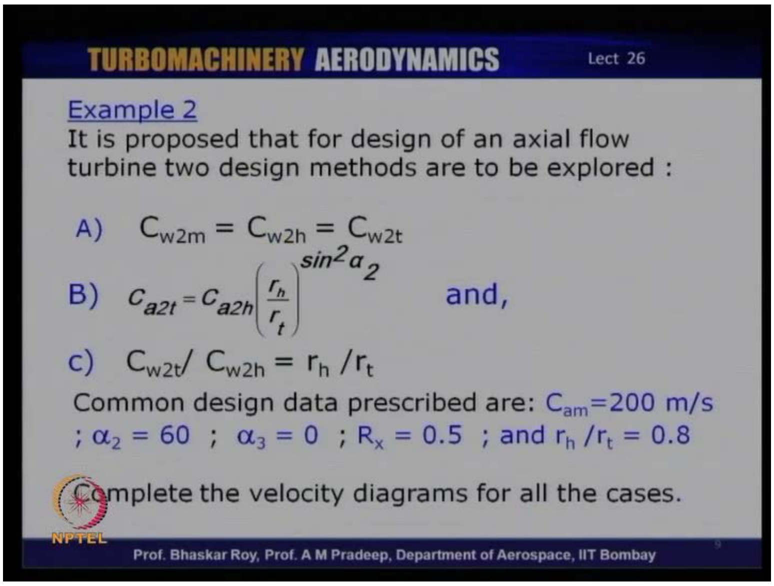

Now, if we go onto the second example in which, the problem statement reads that it is propose that for design of an actual flow turbine two design methods are to be explored. Now, first design method that is prescribed is C W 2 m is equal to C W 2 h that is equal to C W 2 t; that means the whirl components at hub mean and tip are equal to each other. Now, this type of design is what we have called earlier solid body essentially design; that means the fluid behaves more like a solid body and correspondingly the whirl component everywhere are same.

The second design that is prescribed is where C a 2 is equal to C a 2 hub into the radius ratio hub to tip radius ratio to the power sin square alpha 2, which somehow tries to make use of the constant alpha 2 prescription and that is your Case B. The second design that is suggested here in Case B, and incase C, we have C W ratio C W 2 t to C W 2 h has equal to the radius ratio r h by r t.

Now that, if you remember is nothing but you free vortex design. So, we have three design that is suggested for design of an actual flow turbine - one in which the flow behaves like a solid body; the second one in which one may use the alpha 2 equal to constant that is constant nozzle angle prescription and Case C is which resembles of that of a free vortex design.

What is prescribed are some common data and these are the actual velocity at the mean is prescribed as 200 meters per second; entry alpha 2 is 60 degrees; exit alpha 3 is 0. The degree of reaction is 0.5 at mean and radius ratio prescribed is 0.8. What is asked for is complete the velocity diagrams for all the cases. The velocity diagrams are asked for because those are the velocity diagrams based on which final blade shapes would be created. So, the velocity diagrams would give a fairly good idea about the blade shapes that are being created by three cases - a b and c.

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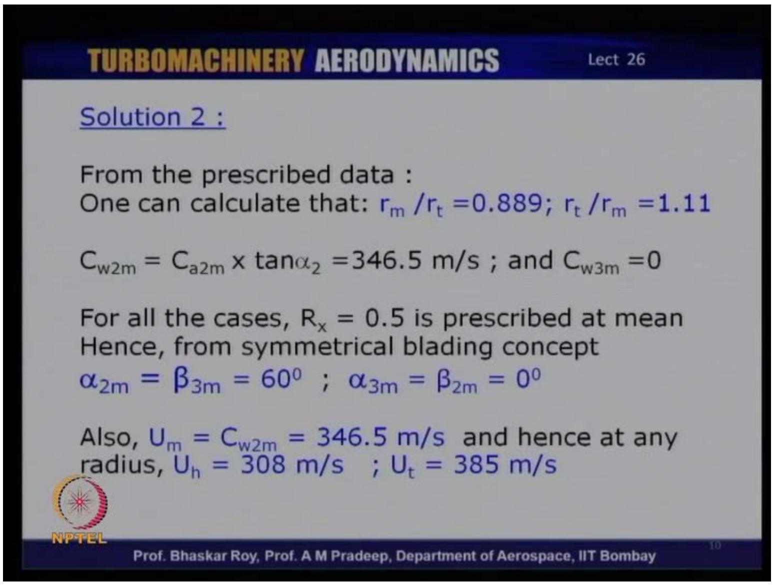

Let us look at how to go about finding a solution to this particular problem statement. From the prescribed data of the example 2, one can calculate that radius ratio r m by r t would be 0.89 and r t by r m would be 1.11. This is calculated from the hub to tip radius ratio that is prescribed in the problem, and then, the whirl component at mean C W 2 m can be found from the mean velocity diagram that is a C a 2 into tan alpha 2 and that gives C W 2 m equal to 346.5 meters per second and it is prescribed that alpha 3 is 0. So, C W 3 m would be 0.

Now, C W 3 m equal to 0 is what we had done in the first problem also, where it is prescribed that C W 3 m could be given as 0 or alpha is given as 0. This is a fairly standard prescription for many of the designs, because what happens is, when the flow is going out of the turbine quite often, the prescription often encourages that the flow going out of the turbine does not have any whirl component, because the whirl component going to going out of a turbine typically of a single turbine or a multistage turbine, last stage would be quite useless.

So, typically of a turbine it is quite often unless you know it is one of the earlier turbines are one of the middle stage turbines. The prescription quite often comes with alpha 3 equal to 0 which leaves 0 whirl component, and if the flow is going in to a nozzle or going into exhaust, any whirl component present is quite useless, only component that is useful for nozzle effect for thrust making is the axial component. So, giving a prescription of whirl component 0 is pretty much a practical and standard prescription for turbine design as I mentioned, unless you are designing a turbine, which is one of the middle stages of a multistage turbine.

So, as we have seen in both the problems C W 3 and alpha 3 of the prescribed to be a 0, and as a result of which, the problems does become a little simple, but the prescription is realistic it is not really idealistic. Let us get back at the problem. For this particular problem statement, it is given the degree of reaction r x is 0.5. Now, that means, it brings us back to the symmetrical balding concept that you may have done earlier and certainly done in some detail in axial flow compressors.

So, the moment you put a degree of reaction 0.5, the symmetrical bleeding concept comes in, and then, you have at the mean, alpha 2 m equal to beta 3 m that would be equal to 60 degrees as prescribed and alpha 3 m equal to beta 2 m equal to 0 degrees as prescribed. This of course, makes the problem a little simple to handle. However, many turbines in the past and the early days of turbine design have been used, using these kind of a somewhat simpler design prescriptions and those turbines were a operating quite well.

It makes the designers job definitely a simple and a probably analysis also become simple in those days and long back thirty forty years back if you may remember, the aid from a computational fluid dynamics was not available, and as a result, the refinement that is possible in today's turbine design was not really available in those days, and as a result, somewhat simpler design prescriptions were often used for design and those were functional, they worked fine cell. So, a similar somewhat simpler design prescriptions has been also prescribed here.

Now, the blade velocity U m would come out to be same as a C W 2 m because u r beta 2 m is 0, and as a result of which, 346.5 meters per second as calculated just a little above, and at any radius, we can now calculate the blade velocities from the radius ratios that we have just written down. So, the hub blade velocity would be 308 meters per second and the tip blade velocity U t would be 385 meters per second. So, the blade velocity is vary all the way from root to tip as a per omega into r concept.

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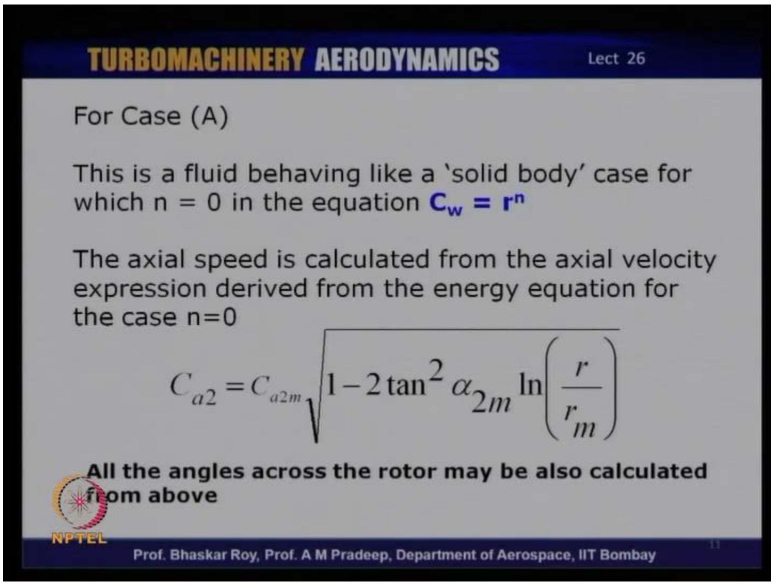

Now, for case A, we have three cases to be actually looked at, and as I indicated, this is a fluid which is a prescribed to be behaving like a solid body for a cases which we have done in the last lecture n equal to 0 for the equation C W 2 equal to r to the power n. Now, when you put n equal to 0, it is a Cases which fluid behaves like a solid body.

Now, the actual speed is calculated from the actual velocity pressure derived from the energy equation for the cases n equal to 0 and this comes out to be C a 2 is equal to C a 2 m whole thing root over 1 minus 2 tan square alpha 2 m into l n radius ratio r by r m. Now, this can be derived; you can said an and derived in the same way we were done earlier for the cases n equal to 0 from the energy equation that we are written down involving the various velocity components.

And you have to put the value of n equal to 0 there and he would arrive at this a solution which we are looking at for a axial velocity at any station with relation to axial velocity at a mean radius along the blade length.

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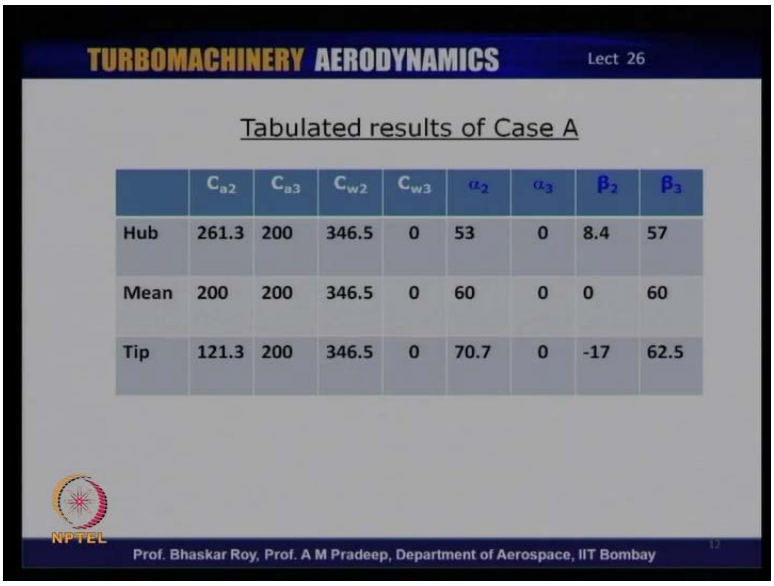

	C_{a2}	C_{a3}	C_{w2}	C_{w3}	α_2	α_3	β_2	β_3
Hub	261.3	200	346.5	0	53	0	8.4	57
Mean	200	200	346.5	0	60	0	0	60
Tip	121.3	200	346.5	0	70.7	0	-17	62.5

Now, using this, you can also calculate the angles across the rotor from the above considerations. If you do that, the solutions that you get for the case A tells you that the actual velocity prescribed at the mean was a 200 and C W 2 at the mean was found to be 346.5. On the other hand, we found the axial velocity is varying from tip to hub and both at the rotor entry as well as at the rotor exit. At the rotor exit, the C W 3 is prescribed to be actually 0, and correspondingly the value of alpha 3 also has been prescribed to be 0. The alpha 2 variation is shown here as part of our results. It varies all the way from hub to the tip. Correspondingly the beta 3 also varies exactly in the same manner from hub to the tip, and the beta 2 values are shown here. It is 0 at the mean as we have calculated, as off we prescribed the degree of reaction being 0. However, there is a small value beta 2 at the hub and a small vale of beta 2 at the mean, at the tip that is been shown here.

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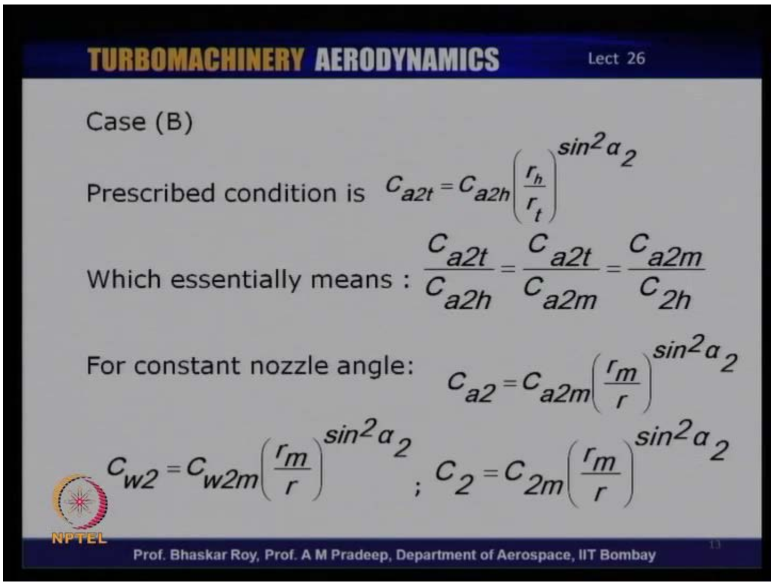

Now, if we move to the results of a case B, the prescribed condition is C a 2 t is equal to C a 2 h into radius ratio r h by r t prescribed here in the problem to the power sine square alpha 2. Now, this of course, brings us to the fact that all the velocities at the tip and hub and mean can be the ratios of them can be put down as equal to each other. All of them would be equal to some relation to alpha 2.

Now, this allows us to write down that far constant nozzle angle, which is the prescribed case B that we were looking at. C a 2 can be now written down as C a 2 m into radius ratio r m by r to the power sine square alpha 2, and in case of C W 2, that would be C W 2 m to the into radius ratio r m by r to the power sine square alpha 2 and C 2 is equal to C 2 m to the multiplied by radius ratio r m by r to the power sine square alpha 2.

So, far constant nozzle angle case, all the velocity C h 2, C W 2 and C 2 which is the absolute velocity can be found from the mean values, that is, at the mean radius to hub to tip at any radius by using this radius ratio concept.

If we do that at the station 3, at the exit of the rotor, it is prescribed that alpha 3 is equal to 0 and C W 3 is also equal to 0. The expression for axial velocity comes out as we have done in the last lecture a C a 3 square is equal to C a 3 square 3 C a 3 m class twice U m C W 2 m to multiplied by 1 minus radius ratio to the power cos square alpha 2. Now, this allows us to calculate C a 3 at exit of the rotor. If we now use the relation that we have done which is essentially for the case B, which is a exit angle from the rotor is held constant from root to the tip of the blade.

Now, this is something which we have discussed in last lecture that, holding the exit angle from the rotor constant from root to the tip of the blade makes the rotor untwisted or very likely twisted. Now, this is important for a stator nozzle blade cooling purpose. We shall be doing a cooling technology from next lecture onwards, but this particular design philosophy of holding alpha 2, 2 equal to constant from hub to tip or root to tip of the blade of the stator essentially caters to cooling technology, and if we apply this, in this present problem what we see is the result that we get for case B.

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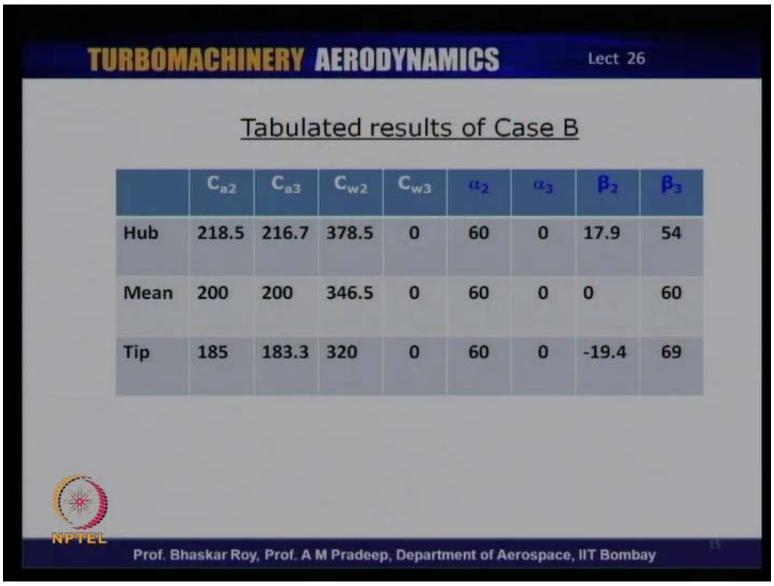

	C_{a2}	C_{a3}	C_{w2}	C_{w3}	α_2	α_3	β_2	β_3
Hub	218.5	216.7	378.5	0	60	0	17.9	54
Mean	200	200	346.5	0	60	0	0	60
Tip	185	183.3	320	0	60	0	-19.4	69

Let us look at the results of Case B. What we see here is the axial velocity is now vary all the way from hub to the tip. At the hub, it is 218.5. At the mean, it is prescribed as 200. So, the variation of axial velocity at the entry as well as at the exit is quite pronounced from hub to tip. The values of C W 2 are also variables from hub to tip point. Substantially C W 3 is being held constant; alpha 2 by prescription is held constant; alpha 3 by prescription is 0.

We get a variation of beta 2 from 17.9 2 minus 19.4 and we get a variation of beta 3 from 54 to 60 nine from hub to tip. So, these are the results of the Case B which is of a constant alpha 2 from hub to the tip of the stator nozzle. Now, we can move to the Case C. Now, Case C is what we had seen was actually the free vortex design. Now, the free vortex design as we have mentioned before is not the most popular design for actual flow turbine even though it is a very popular design for axial flow compressors.

For turbine, it is not the most popular design, but it is the simpler design it of course works. If you make actual flow turbine with a free vortex design, it will surely work; there is no reason why it should not work, but it is not the most popular design today, and ever since the cooling technology came into the market, the free vortex design has been essentially replaced by the constant alpha 2 design which is the more popular design philosophy for turbines essentially as I mentioned to cater to a cooling technology. But let us look at the results that we get for this problem a statement problem to Case C for a free vortex design philosophy.

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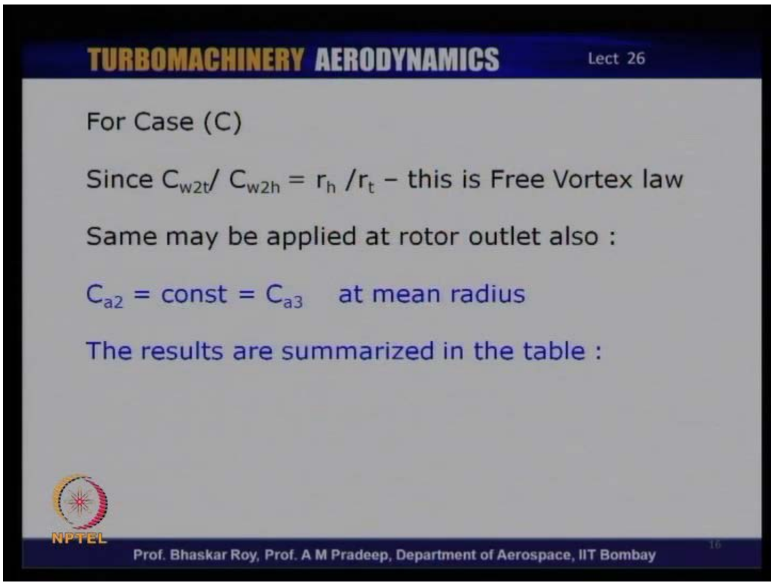

If you apply free vortex design philosophy, the whirl components at tip and hub the ratios are directly related to the hub to tip radius ratio. Now, if we apply the same at the outlet also, C W 2 also is held constant as per free vortex principle across the blade at mean various. So, C W, C a 2 is equal to C a 3, and if you apply all these, in the, as per the free vortex law, we get a set of results directly as per very well known free vortex law prescriptions.

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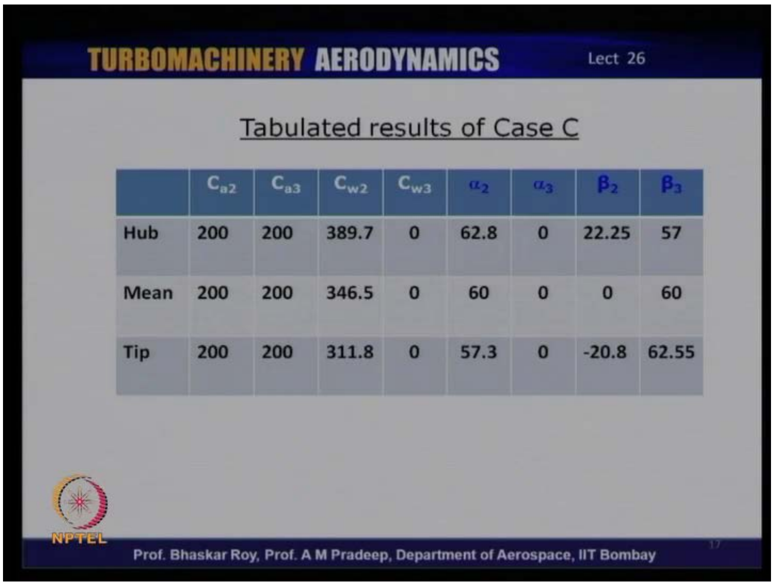

The results that we get that the axial velocities are held constant from hub to tip as well as across the rotor. C W 2 varies substantially from hub to the tip as per free vortex law and which would tell you that you would end up getting a substantially twisted blade. C W 3 is being held constant. So, the trailing edge would be rather leaner. On the other hand, the value of alpha 3 is 0 corresponding to the prescription. Alpha 2 varies from hub to tip and the C W 2 variation shows that, and then, of course, you have the variation of beta 2 which goes minus at the tip and this is something that comes out of the free vortex design, and as a result of which, you get a variation of beta 3 which also varies from hub to the tip of the blade.

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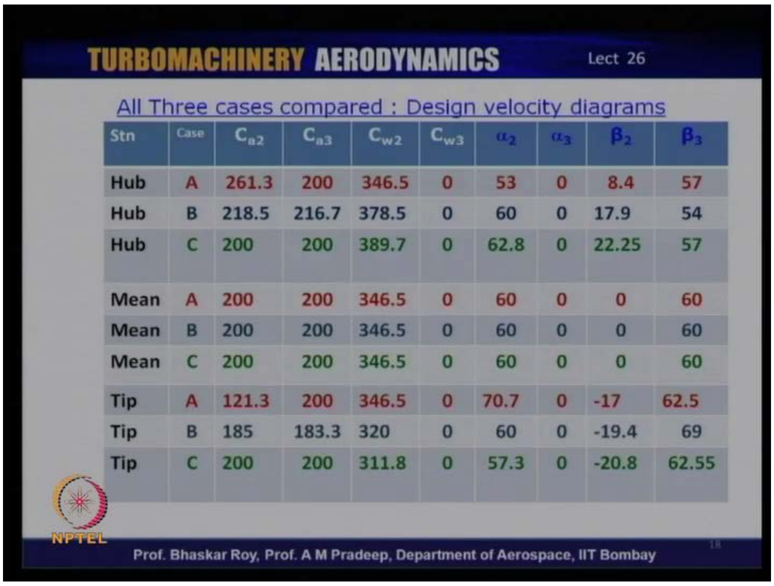

Stn	Case	C_{a2}	C_{a3}	C_{w2}	C_{w3}	α_2	α_3	β_2	β_3
Hub	A	261.3	200	346.5	0	53	0	8.4	57
Hub	B	218.5	216.7	378.5	0	60	0	17.9	54
Hub	C	200	200	389.7	0	62.8	0	22.25	57
Mean	A	200	200	346.5	0	60	0	0	60
Mean	B	200	200	346.5	0	60	0	0	60
Mean	C	200	200	346.5	0	60	0	0	60
Tip	A	121.3	200	346.5	0	70.7	0	-17	62.5
Tip	B	185	183.3	320	0	60	0	-19.4	69
Tip	C	200	200	311.8	0	57.3	0	-20.8	62.55

So, you have the results of the Case C Tabulated here, and then, we have three Cases – a, b and c these variations can now be all put together into one table which are essentially tries to compare the 3 Cases – a, b and C, and as you can see the Case A is given in red, the Case B that is a constant nozzle angle is given in b and the free vortex design is given in Case C and all three of them are brought together. If you sit down, use the velocity is that I given the angles that are given, and if you draw the velocity triangles of all the cases, you will probably get a very clear picture of what kind of blades actually come out of the three-dimensional blade shapes that should come out of the three Cases that are prescribed here. The three cases that are prescribed here had certain commonalities, that is, the mean actual velocity prescribed by 200. The exit the angles were prescribed to be 0. The whirl components at the exit were prescribed to be 0.

So, with those common prescriptions, we try to put together; the blades that would come out even with those commonalities, and we see that three completely different blade shapes are likely to result from three cases that are prescribed here for axial flow turbine design. So, as I mentioned, you can probably sit down and actually draw the velocity triangles and you would find that three different cases or three different blade shapes and he would indeed need to choose different aerofoil shapes, different blade sections from hub to tip for the each of these three cases. So, you end up having three completely different blade shapes for three different design philosophies even though we started out with a common data prescription for all three cases. So, this is an example which tells you with certain simplifications or simplified problem. It still tells you that, if you have three different design philosophies, you end up with three completely different blade shapes. I will now leave you with a few problems which you can sit down and solve for yourself and get a feel of the numbers that come out of solving of examples problems that are prescribed with numerical values. So, let us look at some of the problems you can solve for yourselves.

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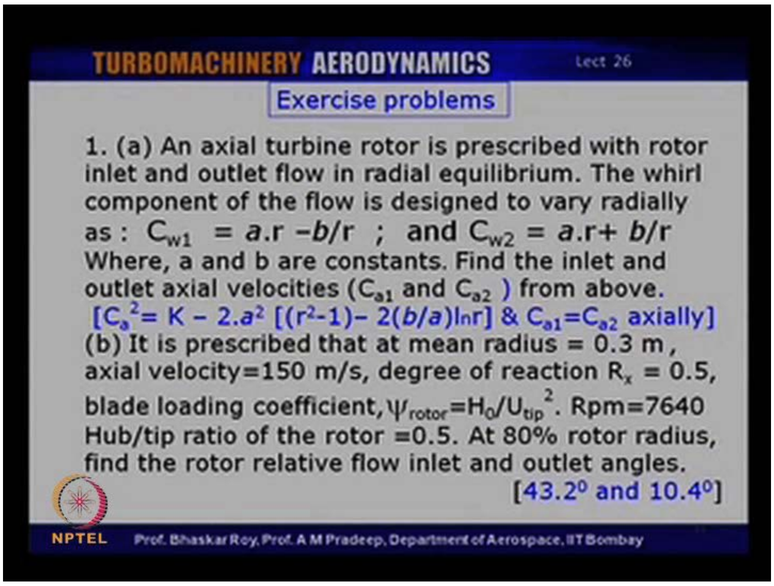

The first exercise, exercise, problem, the problem statement reads that an axial turbine rotor that is prescribed with rotor inlet and outlet flow in radial equilibrium, which means the static pressure and the dynamic pressure are balanced at the inlet and outlet of the rotor. The whirl component of the flow is designed to vary radically as per this prescription as C W at the inlet as a r minus b by r and at the outlet as a r plus b by r. Now, a and b are the constants, and what is required for you to find is find the inlet and outlet exit velocities and the expressions for those velocities.

In this case, you can see the answers given here and the actual velocity is of course would remain constant across the rotor. So, we are dealing with rotor only. So, the problem statement is essentially for rotor. Part b of the problem is - it is prescribed that at mean various given value is point 3 meters. The actual velocity is 10 meters per second and the degree of reaction is 0.5. The blade loading coefficient is prescribed as, as, per the definition, psi rotor is equal to work done, specific work done 8 0 by U tip square and the r p m in 7640 rpm.

The hub to tip radius ratio is given as 0.5, and at 80 percent of the rotor radius, it is required for you to find the rotor relative flow inlet and outlet angles. So, what you are required to find the beta values of a beta 2 and beta 3 for the particular problem statement that is given here. Now, the answers given are 43.3 degree and 10.4 degree for beta 2 and beta 3. So, you can try to sit down and see whether you can arrive at those answers.

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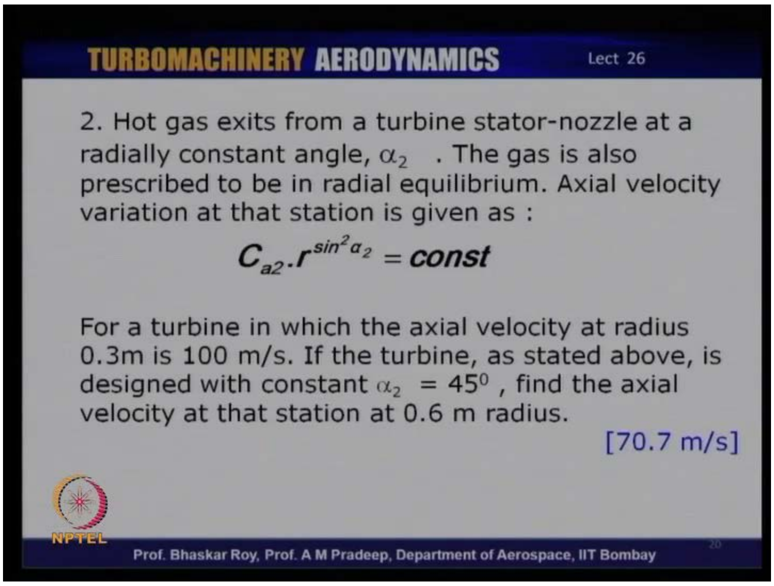

The second exercise problem that is given is the gas exits from the turbine stator or nozzle at a radically constant angle alpha 2. So, it is a constant nozzle exit angle problem. The gas is prescribed to be in radial equilibrium. The axial velocity variation at that station is given as C a 2 in to r to the power into sine square alpha 2 equal to constant. This is what we have done in our lectures also, and for a turbine in which the axial velocity at the radius, 0.3 is a again prescribed 100 meters per second, and if the turbine has stated above is designed with a constant alpha 2 equal to 45 degree, find the actual velocity at that station at 0.6 meters radius.

Now, the answers given here is very simple and that is 70.7 meters per second. So, it is a constant exit, stator exit angle problem and you have to apply the relations that we have done in the lecture or in the earlier problem that has been solved for you.

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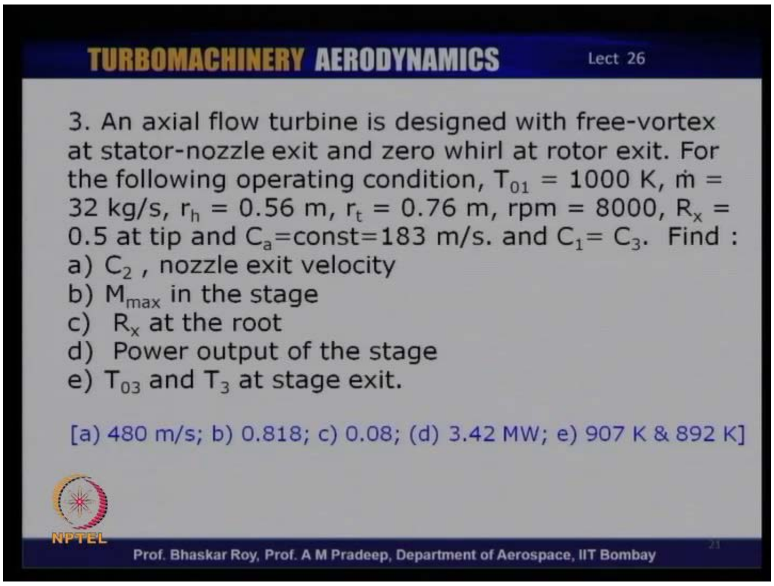

The third and the last problem that is prescribed for you to solve is an axial turbine is designed with free vortex at stator nozzle exit and 0 whirls at stator at rotor exit. So, it is a free vortex problem applied at stator and nozzle exit and a rotor inlet. So, the station between the stator and the rotor carries free vortex prescription. For the following operating condition, that is, at the entry t 0, 1 is equal to 1000 k mass flow is given as the thirty 2 kegs per second. The hub radius is 0.56; the tip radius is 0.76 meters; rpm prescribed is 8 thousand; the degree of reaction is point 5 and a actual velocity is constant that is 1 into 3 meters per second, and it is prescribed that the inlet and exit absolute velocities are equal to each other, that is, c 1 is equal to c 3.

You are required to find C 2 that is the nozzle exit velocity. As you know, it expands ha hugely from C 1 to 2, and then, you are required to find the mach number, maximum mach number at the stage. In this particular stage, typically it is most likely to be a somewhere in the nozzle exit, and then, the reaction at the root, the power output of this particular working turbine and t 0 3 and t 3 at that stage exit. So, these are the numerical values that you need to find out of this prescribed problem.

The answers solutions that are given here is that the nozzle exit velocity C 2 is would be for in 80 meter per second. The maximum mach number in this stage is so solved as point 0.818. The reaction at the root is 0.08, and you remember at the root, it is quite often specially free, free, vortex. It is likely to be very close to 0 and 0 of course would mean an impulse turbine, and we are looking at a problem in which, the solution actually comes pretty close to giving you an impulse station, impulse section at the root of this particular turbine, and then, the power output are work done for this particular rotor given the mass flow is 3.42 mega watts, and the temperatures at the exit t 3 is 907 and the static temperature t 3 is 8 892 k.

Now, you can sit down and try to solve this problem and see whether you can come. You can standard values of ah gas constant r, that is, 247 joules per kg k and value of C p as thousand 147 joules per kg k. So, you can use those standard values to solve this problem in which, numerical are given and you are required to find the certain prescribed velocities, mach numbers, work done and the exit temperature. So, I leave you with these problems for you to solve yourself so that you can get a feel of the numbers the typically come out of axial flow turbine design. So, some of these problems would give you an idea how the turbine designs indeed proceeded with, and what kind of numbers you get? What kind of variations? You get a you get a feel of the numbers by solving these problems.

In the next class, we will be looking at turbine blade cooling, because in this class and in the earlier lecture, we had looked at the design philosophy of alpha 2 is constant from root to the tip and we have stated again and again that this particular design philosophy essentially caters to turbine blade cooling. In the next lecture onwards, we will devote ourselves to looking at this turbine blade cooling technology and how it impacts the turbine blade, the turbine blade shape, and essentially, the aerodynamics or the aero thermodynamics of the flow over the turbine blades is very strongly impacted, and essentially, the aerodynamics of the blade changes hugely by application of cooling technology.

We will look at various cooling technologies and how do they actually impact the turbine design of modern actual flow turbines specifically these cooling technologies are very widely used in aero engines, and we will look at some of the typical examples of these applied cooling technologies in turbine, actual turbine, rotor and stator. So, we shall be doing turbine cooling technologies from next lecture onwards.