Wind Energy

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Lecture 31: Off-design performance issues

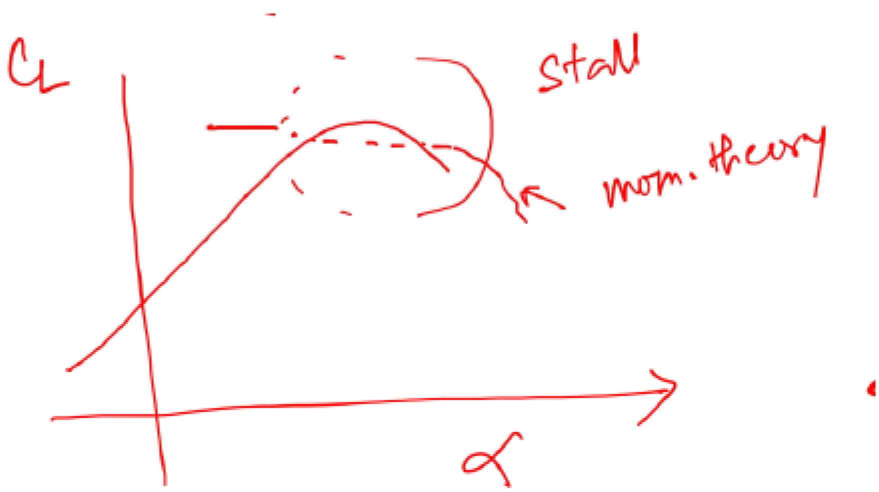
Welcome back, so, let us continue our discussion on this aerodynamics analysis in the past perspective of design consideration, so, what we have kind of talking about we are looking at a different aspect of design consideration obviously, all this analysis is based on our simple momentum theory, one-dimensional momentum theory, then blade element theory, combining the blade element momentum theory. And, then we looked at these different cross-sectional areas. They are finding the induction factor, then Cl, and then the profile, especially the chord length. And that is very important because the chord length for the rotor blade actually varies from hub to tip. and there is also some other consideration which comes into the picture is the uh solidarity of the material and that those details will look at further so now what we can see uh some of design performance issue so the of design performance issues what of design performance issues. So, this is nothing but this off-design performance issue.

It kind of, it appears because when a section of the particular blade uh has a pitch angle or flow condition very different from the design condition that means we have designed the blade we have designed the complete system based on certain conditions and then they vary during operation by a large margin that time the performance actually degradation obviously, This could be the rotor blades tall. This could be highly loaded condition. This could be wind gust. This could be due to heavy wind directions or certain things.

So, all this could be possible reason for having this kind of off-design performance, but then how we can tackle those issues. So, that is what we can talk about it. Now, while talking about that, So, as I said the issues may come from all this during actually operation what may possibly occur. So, I mean simple thing if you look at this Cl versus alpha, this is Cl versus alpha curve which is typically goes for particular aerofoil. If you see this, I mean, install region, this is my stall region, where there could be multiple solutions.

Because this is from, let's say momentum theory, the stall region, we have multiple solutions, this solution, that solution. So, the correct solution should be such that which maintains the continuity of the angle of attack along the blade span. So, here one can have multiple solutions but correct solution must be that which maintains the continuity of the alpha along the blade span. So, this is because you have, I mean, essentially, this is primarily because you have multiple solution to blade element momentum equation. So, that's why this could possibly happen.

I mean, due to multiple solution of blade element momentum equations. So, that's what you can end up getting this kind of graph, which may be a little problem or some kind of an let's say of design performance issues be reason behind that then one can have flow status so that means over turbine so that means someone can say that the i mean Usually, the measured turbine performance or the wind turbine performance closely approximate the results of beam theory at low values of axial induction factor. Obviously, the momentum theory doesn't hold good beyond A equals to 0.5. So, the axial induction factor greater than 0.



5, it doesn't hold good. Because what happens is that the wind velocity in the far wake would be negative. So, that's the problem that one would have. Usually, in practice, axial induction factor, as the axial induction factor increases above 0.5, the flow pattern to the wind turbine become much more complex than those predicted by momentum theory.

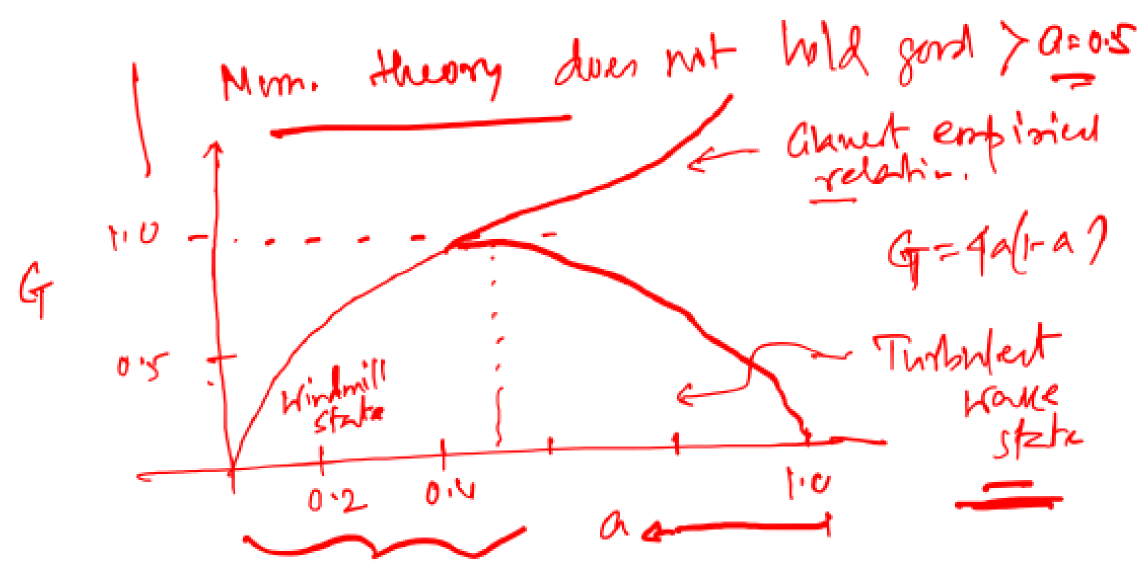
So, that means there is a restriction on a value because whatever you get from your design consideration. That has to be somewhere less than 0.5. If it increases beyond certain limit, then the flow conditions become different. And so what, I mean, you can expect, I mean, essentially if someone plots some graph, this is some kind of a behavior of that, let's say 0.

2, 0.4, 0.6, 0.8. one and then you get 0.51 and this is your c t thrust coefficient so the ideal thing is that it is at 0.5 is the maximum so somewhere here is the maximum it goes the peak here and then comes back at 1 here.

I mean, if you draw. Here the city is 4a into 1 minus a. That is the equation it follows. So, this side you can say it is a wind mill state. This side one can say turbulent weak state.

Okay! And, what happens is that there is some empirical relation which goes like that. This is known as Glibert empirical relation. So, this empirical relation. So, what it shows this particular graph is that So typically, the operational states of the turbine are designed in two conditions. One is that windmill state.

Another side is the turbulent state. And, windmill state is the normal wind turbine operating state. And, the turbulent wake state occurs under operation in high winds. Obviously, speed goes high. Then you have higher wakes in turbulence nature.



So, this particular graph here, Ct versus A, it shows the measured thrust coefficient of these operating states. Obviously, this side, the windmill state, if you consider, then that's very nicely described by momentum theory for axial induction factor, which is shown in the windmill state. one can see A is less than 0.5. So, this is the range where we are talking about.

So, this is nicely correlated or corroborated by the momentum theory. But above A equals to 0.5, which is this particular range where the turbulent state, measured data indicate that the thrust coefficient increase up to about 2 or so. So, this actually goes beyond that. So, this is a situation.

But ideally it should come down which doesn't happen. So, this state is usually characterized by large expansion of slipstream, turbulence and recirculation behind the rotor. And, actually what happens is that the momentum theory no longer kind of able to describe the turbine behavior. And, the empirical relationship between CT and the axial induction factor are often used to predict turbine behavior. So, there is a deviation that actually takes place or that actually occurs, which is one of the reason for um this kind of issue which would lead to again the performance related issues which is i mean going ahead from your design situation then we can let's say so now we can talk about the rotor modeling part rotor modeling for this turbulent wake state.

Okay. So, that could be another issue. So, what we have discussed so far is the or the analysis that we have talked so far which uses the equivalence of the thrust forces which so the thrust forces coming from the momentum theory and blade element theory. Okay. And, so that kind of to determine the angle of attack of the blade. So, what happens is that so this whole thing would determine alpha and then from alpha to rest of the parameters like that.

But, what happens at turbulent wake state, this is no longer valid at turbulent wake state. So, that becomes a problem. So, this first calculation is no longer valid in that state. So, in these cases the obviously, the typical solution may not be the correct one which could define the airfoil lift cup so that is the possible so here again some kind of an as we have seen in this picture here, that some kind of an empirical relationship by Gluert, which is used and that relationship, so that includes that empirical relationship includes your axial induction factor a coefficient Ct along with your blade element theory. So, also it includes deep losses.

So, that means all is under consideration. So, that's how you estimate A is 1 by F point one four three two not three six four two seven eight eight nine minus city so this is our this was kind of an this equation this was developed by And that's why this relationship is known as Glouett empirical relation. So, this equation, obviously, the validity is for A greater than 0.4 or equivalently, one can think about what equivalently Ct greater than 0.

$$a = \left(\frac{1}{F}\right)\left[0.143 + \sqrt{0.0203 - 0.6427(0.889 - C_T)}\right] \quad \ldots (51)$$

96. So, that means that maximum CT1 and then it's supposed to fall down in the turbulent weak state. So, that is kind of taken care of. So, this relationship is also determined for the overall thrust coefficient for the rotor. So, this has been extended for calculating overall thrust coefficient. Obviously, one can think about it applies equally to equivalent local thrust coefficient for each blade section.

So, what we can have the local thrust coefficient, which is let's say CTr is d of Fn by half rho u square 2 pi r dr. So that's how it's in each annular section that is what you get, okay! now, we can use or replace this normal force from blade element theory, so, we can use that equation from blade element theory the normal force so which is equation that you have which is equation basically equation 2020 I mean 22 if you correctly so, this is so, the normal force equation from from 22 equation which is from blade element theory. So, what we can write by sine square phi. So, the solution procedure can then be modified to include heavily loaded fragment. So, earlier the solution procedure that we have discussed then that has to be changed for.

$$C_{T_r} = \frac{dF_N}{\frac{1}{2}\rho U^2 2\pi r\,dr} \quad \text{section} \ldots (52)$$

$$C_{T_r} = \sigma'(1-a)^2\left(C_l \cos\varphi + C_d \sin\varphi\right)/\sin^2\varphi \quad \ldots (53)$$

So, what we can say the solution procedure needs to be changed for heavily loaded turbine. The easiest procedure to use this iterative method so obviously easiest procedure is to use iterative method that is our method number two that starts with the selection possible values of a and a prime and once the angle of attack Cl Cd have been determined the local thrust coefficient can be calculated using this equation so then once you using this method you start with a and a prime to get Cl Cd alpha then CTr can be used equation 53 to evaluate that and then one can check the local if city is less than 0.96 then the previously derived equation can be used if it is greater than 0.6 then you can use this to estimate for this loading of the turbine, so, and then subsequently you can use the other equation for rest of the calculation so that is another thing that can happen and which can lead to this kind of of design performance issues that means things are um things gets deviated from the design consideration Then another possible could be blade honing and top axis holes.

So, this is also possible. So, here the reason is that what we have been talking about is that the essentially our analysis primarily assumes uniform wind velocity which is approaching towards the turbine or the rotor axis and the blade ideally rotating. So, what is, the situation here that we, so all this theoretical analysis that we have done, it's assuming you have a rotor blade and the wind comes uniformly towards that and the rotor rotates. But, what happens in situation is that actually in reality, in practice, this really be the case because you have winds here.

You have. Wind shear. You have your error. Okay. You have.

Vertical wind components. In reality. Vertical.

Vertical. Wind. Components. Okay. You have. turbulence okay and blade coning, okay so, you have all these things uh winds here essentially will result in wind speed that vary with height across this, so, wind shear will come because you have this kind of an so because of that you will have the winds here across the rotor digs. Wind turbine often operate with a steady state or transient EI error so, that misalignment of the rotor axis and the wind direction about the vertical EI axis of the turbine. So, obviously what EI error does is that it results a flow component essentially it results a flow component perpendicular to the rotor axis component perpendicular to rotor axis or rotor disc is much more. So, the wind at rotor may have a vertical component, especially because of your sides might have some terrain and things like that.

Turbulence again results in a variety of wind conditions over the rotor. So, turbulence also provides a variety of wind condition. So, that is also there. then the angular position of the blade in the rotor plane is called the azimuth angle and is measured from some suitable reference. Each of these issues, I mean, things that we have talked about, wind shear, rear error, vertical wind component, turbulence, and all these, actually, this can result in Conditions at the blade vary with the blade azimuth angle.

Finally, blades are often attached to the hub at slight angle to the plane perpendicular to the rotor axis. So, blade cooning may be done to reduce bending moments in the blade or to keep the blades from striking the tower. So, that's the major issue because the way the angle, the azimuthal angle has been there and that can vary for these conditions which can lead to that kind of situation. So, since the blades are attached to the hub, so this kind of honing is required to be done to reduce bending moment.

So, blade honing it reduces bending moment. Obviously, in our rotor analysis, all of these that we have discussed, these are situations which are usually handled in some kind of approximate geometrical transformation. And, this blade coning is handled by resolving the aerodynamic forces into components, components that are parallel and perpendicular to the rotor plane. So, similarly top axis flow is also resolved, is also handled by resolving by resolving into components as mentioned above. That means also the off axis flow to be tackled by resolving the aerodynamic forces in parallel and perpendicular component to the rotor plane. So, then the rotor performance is determined by the variety of rotor azimuth angle.

So, rotor performance is determined by the variety of azimuth angle. So, the axial and in plane components of the flow that depend on the blade position results in angle of attack and aerodynamic forces that fluctuate cyclically as the blade rotates. Essentially, what happens is that the BAM equation, so the BAM equation must include this blade honing and other techniques to deal with top axis flow. So, what it requires that the equation that so, we have initially started with the fundamental or basic equations, then the modification that we are bringing in that is how to tackle different situation. This is another situation this blade coning or op-axis flow that can be tackled by bringing in this modification in the BAM equations and also other techniques which we will discuss later when we will talk about this dynamics of the components and things.

So, we will stop the discussion here and continue the discussion in the next session. Thank you.