Wind Energy

Prof. Ashoke De

Department of Aerospace Engineering, IIT Kanpur

Lecture 34: HAWT optimum performance analysis

Welcome back, so we'll continue our discussion on this rotor performance or optimum performance of the turbine wind turbine, so, essentially we are talking about the horizontal axis wind turbine and their performance and dependency of the performance on on different different factors, so, now what you want to see the basically optimum performance. That is what we want to look at it. But, essentially what we want to look at the effect of drag and blade number. So, we have so far looked at different parameters because theoretically you can have maximum power coefficients which is as per base limit but ideally that doesn't happen because you have keep losses you have your error you have other aerodynamic losses also i mean in a single word one can say that the in operation performance always gets affected due to the off-design issues. So, that we have talked about. Now, we want to look at what would be the I mean this drag and the blade number or number of blades that you can have and what would be the impact of those parameters.

So, that is what we are going to look at it. So, actually we have already looked at that that tip loss also a function of number of blades which actually reduce Cp which is your power coefficient. Okay. So, we have already looked at this thing that performance gets affected and then what we can find out the maximum maximum available power coefficient so for any turbine with an optimum blade shape along with the finite number of blades and their aerodynamic drag these are all can be estimated by empirical formula so which was given by Williams in 1976 Williams et al 1976 and so that is given that Cp max one can have 16 by 27 lambda lambda plus 1.

32 lambda minus 8 by 20 square by b to the power two-third minus 1 minus 0.57 lambda square C L by C D lambda plus 1 by 2b. So, this data is quite accurate, this fit of the data accurate to within 0.5% of the speed ratio. ranging from 4 to 20.

And, also Cl by Cd varies between 25 to infinity. And obviously, the number of blades would vary 1 to 3. So, for this range of data, this fit is quite good. which can have a variation even less than, I mean, equal to 0.5% of tip speed ratio where you can have this power.

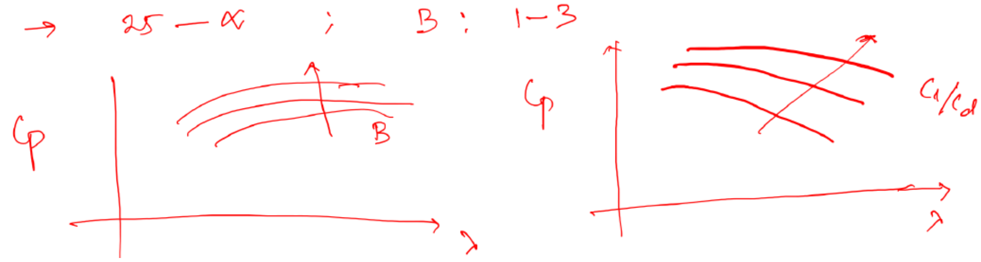
So, now one can show for if you plot lambda in the tip speed ratio and Cp this side, then you can get different curve like that. And this could be increasing b as the number of leads increases different kind of plots here also you can have let's say similarly for lambda variation and you can have Cp you can have Cp and then you can have different curve for increasing Cl by Cd. So these correlations actually can provide you different kind of variations and that also so these empirical formula which are available they are quite useful in terms of design. So, obviously, when you talk about the ideal conditions of ideal operating conditions on the performance level, under ideal conditions, which include with rotations, number of blades, all these are going to take into account this kind of situation to handle and so now what we want to also quickly touch upon that the like for this aerodynamic design different aspects okay so for example one can say that we can see computational expert. So, what we have discussed so far, the performance and all these things, those are under steady state aerodynamics.

Max. available Power coeff. (Williams et al., 1976)

$$C_{p,max} = \left(\frac{16}{27}\right)\lambda\left[\lambda + \frac{1.32 + \left(\frac{\lambda-8}{20}\right)^2}{B^{2/3}}\right]^{-1} - \frac{(0.57)\lambda^2}{\frac{C_l}{C_d}\left(\lambda + \frac{1}{2B}\right)} \quad \dots \text{(96)}$$

→ accurate to within 0.5% for tip speed ratios (4–20)

L: $\frac{C_l}{C_d}$ → 25 – ∞ ; B : 1–3



So, we have also achieved or obtained some of the results uh also loads and all these things obviously here we are talking about the aerodynamic load under steady state conditions however actual operation actual operation of turbine is unsteady okay so obviously there are dynamic effects which can increase loads okay or also which can decrease power i mean obviously when we exposed to some kind of a transient loading conditions and things like that uh so now here we talk about how you can analyze those kind of things but obviously the approach that you need to adapt the computational approach that means you need to solve the complete turbine or the analysis of the turbine using this kind of I mean you need to have this kind of methodology. Now, one aspect of it you can have let's say non-ideal steady state aerodynamics issues. So, the steady state that influence wind turbine behavior, it include the degradation of blade performance due to surface roughness, the effects of stall on blade performance, blade rotation. So, obviously the performance degradation happens due to surface roughness, stall on blade performance and blade rotation. All of these are kind of taken into, so, obviously what happened is that the blade surfaces roughened by the damage and debris can significantly increase drag and decrease the lift on the aerofoil.

So, the surface roughness that we are talking about, so this effect is increasing the drag Okay. And obviously, the lip will decrease. So, once the lip decreases, obviously, this is going to impact the rotation of the blade and indirectly the going to affect the power generation. Now, there are some database which shows that it can this power so that means power would go down which is almost 40% reduction in some airfoils under certain conditions though. So, what is the remedy here? The remedy here is that you need to have frequent blade repair and cleaning.

That is one option is that or use of airfoils that are less sensitive surface roughness so that means when you have this effect you also can have some remedy or mitigation technique to come out of that thing also what you can do is that when the blades or parts of the blades are installed region, the fluctuating loads may result also. So, on stalled controlled horizontal axis rotor, much of the blade may be stalled under certain conditions. So, obviously the stalled aerofoil would not exhibit some simple relationship between the angle of attack and the aerodynamic forces which are obviously evident from the lift and drag coefficient data. Top of that you can have turbulent separated flow conditions which can occur during stall can also induce rapidly fluctuating flow condition. Obviously, the stall and or turbulent condition increase the load on turbine.

So, what you need proper airfoil selection to be made so that you can have delayed stall or may produce more power than expected. Also, different wind conditions, it should be able to kind of adjust to the situation. So, these are non-ideal steady state aerodynamic issues. Then, you can have turbine wake, which we have talked quite a bit of details. But, the theory that we talked about, the BEM theory, which gives us the induced velocities due to power production and the rotation of the turbine wake and expanding wake downstream of the turbine.

However, the actual flow field is much more complicated. So, though we have beam theory plus wake rotation correction, all these are there, but still actual flow field is much more complicated. The actual flow field is much more complicated. So, then obviously these complicated flow patterns affect the downstream turbine result in skewed wake, which causes increased fluctuation loads on the other turbines, especially in the cluster configuration and all these things. But, one thing is that this wake can be classified into two segments.

Obviously, one could be classified, so if a turbine is here, and this is the flow then there could be wake I mean basically creating condition. So, just near the turbine one is the near field wake or near wake another is the far wake. So, this could be near wake and this is far wake. Okay. So, the difference essentially between this near and far wake is a function of spatial distribution and intensity of the turbulent in the flow field.

So, the near wake would have which is close to the turbine downstream location which will have more I mean impact of the flow field more fluctuations and all these things but far wake would be little bit more calm and the effect of turbulent intensity gets reduced. Obviously, the wake actually provides the conservation of angular momentum. Apart from these vorticities which are coming out from the trailing edge of the blade, also the hub there are going to be vortices which are going to be generated deep vortices could be there so the this weak structure have all sort of apart from this so essentially if you have an aerofoil like that which is in a finite blade so this is your trailing edge and this is leading edge So, the leading edge vorticity is one of them, sub-vortex shedding, then hip loss. So, all these are having this vortex or circulatory flow field. behind the turbine and which is kind of considered them under the one umbrella of weight.

So, near field is more intense, you have more effect here as you go further downstream towards this when you call it as a far weight. So, they have less intensified turbulent fluid. So, obviously these are effect of the turbulence and this can have impact of this. So, this is going to increase load.

As simple as that. That means one has to consider that while considering the design and all this. Another important effect occurs with top axis, that is those whose direction, those whose direction is not perpendicular to the plane of the rotor. So, up axis flows whether due to EI error or vertical in a skewed wake in which the wake is not symmetric with the turbine axis. So, that could be this sub-axis flows of axis flows which are caused due to Eeyore or vertical wind components that has produced skewed wave. So, that means the skewed wave is not symmetric.

What happened is that the skewed wave result in the downside or downwind side of the rotor being closer to the tip vortices which is being transported downstream than the upwind side of the rotor. So, this will have higher induced velocity on the downwind side of the rotor. than the upwind fight. What we can have an effect is that so obviously this will lead to higher turbine forces. So, this will have higher turbine forces.

So, that means one needs to have kind of an directions or proper strategy to avoid such situation so that this doesn't include those kind of conditions. Okay. Now, we can have our unsteady aerodynamic effects. So, there are number of unsteady aerodynamic phenomena which have a large effect on wind turbine operation. one of the turbine eddies which carried along with the mean wind cause rapid changes in speed and direction of the rotor disk.

So, this can, these changes cause fluctuating aerodynamic forces increase. So, this unsteady aerodynamic effects will have essentially fluctuating aerodynamic forces, peak forces, blade vibration, significant material fatigue, et cetera. Moreover, this transient effects of tower shadow, dynamic stall, dynamic inflow and rotational sampling change turbine operation in unexpected ways. Obviously, any unsteady condition that would be there, that can change this whole aspect of this operational performance and all these things. So, obviously, what happens is that, so that means you have this, I mean, you have this transient effects on these towers and all these things.

So, you can have all this occur at rotational at single one or multiple ones so effect that occur once per revolution are often referred to as a having frequency of one the effect that occur at three or n times per revolution could be 3p or np so all these 1p or 3p so now what we refer as a tower shadow which is kind of an... So this refers to the wind speed deficit behind a tower caused by the tower obstruction. So, the blades of a downstream rotor with B number of blades will encounter the tower shadow once per revolution causing a rapid drop in power and B into P vibration in the turbine structure.

So, these essentially have dynamic effect or loading on turbine. Then you have dynamic stall. So, the dynamic stall refers to the rapid aerodynamic changes that may bring about or delay stall behavior. So, this is a rapid changes in stall behavior on blade. So, this happens primarily because of the because of this rotation, so, it primarily as you said that the dynamic stall occurs because you have this airfoils and then you have a kind of an blades okay, so, now what happens that each blade is rotating Okay! they are in the rotation.

So, let's say the flow passes by this about this aerofoil and that somehow due to some change in the upstream flow field or due to the change in the conditions or angular vertex something it experiences stalls. But, these stalls again the blade is rotating in this So this stall is going to cascade to the next subsequent blade, which is in rotation. So, actually what happens in a very simple word, when the stall happens, by the time the next blades come close to that, there is a blockage of the passage, effective blockage of the passage, which can also lead to the stall for the subsequent blades. So, the dynamic stall, if it occurs, then there is a chance or possibility of that is going to cascade to the next blade because of this rotation. So, those kind of situations primarily happening because it's a rotating system.

And, once you have that kind of dynamic stall effect, it's going to have huge impact on the turbine performance because it's going to increase your drag. And, at the same time, there is a possibility because of this vortex shedding and all this, you may end up having high frequency or the...

loading on the structure and all this. So, other unsteady effect also we will talk about in the next session. Thank you.