# Wind Energy

**Prof. Ashoke De**

**Department of Aerospace Engineering, IIT Kanpur**

## Lecture 28: Wake

Welcome back to this particular session. We will continue our discussion on this airfoil and then wick. And to start with or to begin with, why this particular thing is so important, if you recall that we have talked about different momentum theories, the momentum theories with wick rotation. thing here is that since your rotor blades or the turbine blades they are rotating so there would be some weak because anything which is kind of in the body which is rotating and any fluid here in this particular case is here passing over that and then there would be some kind of a flow separation towards the tailing edge and that generates obviously from the tip also because of this rotation the wake actually forms since I mean even nothing happens what happens is that with your what you call if this kind of structure So, if you have this and there are these blades which are rotating, then behind this rotation, and if you have a wind flow like that, so these are the tip. And, because of this rotation, this rotor blade tip behind that, there could be a rotation which would come behind that. So, wake.

is an important aspect of it because that plays a very critical role. Because, if you have too much of weak, which means, I mean, that can affect the subsequent turbines if you are talking about cluster and things like that. So, what we want to look at is the first question which comes is that what is wake? You see here, these are the turbines and behind that this kind of structure. So, this is a ship traveling right to left.

And, you see this structure, this is called wake. So, this you can find in nature in multiple places. Nature, this exists. So, if you talk about the duck swimming in water, you will see this kind of weight. If you see the birds flying in air, you can see this kind of weight.

You can see some kind of weight even the aircraft is flying due to that. So, you have this kind of weight, which is kind of visible in nature and a different form so it just so here this is now let's zoom a bit and try to see so that the same picture here we zoom in bit come close to the or turbine you could see this, so, this is the front row of the or front row of turbine this is the subsequent row and you see this is the problem row after that so, If you think in terms of from perspective, the flow, this particular turbine is exposed to is clean air. So, the air which comes on the surface, whatever, that is the clean. Then behind this turbine and this turbine, they are under the effect of this turbine. this wake is going to impact this turbine and similarly the wake of coupled wake of this is going to impact this turbine, so, the wake is pretty big in size and some of the turbines are sitting directly in it, so, once you have it what is going to happen effectively this is not going to give you the optimal power that you expect to extract out from a particular turbine.

So, maybe the front turbine provides you some kind of power, but the subsequent turbine would not be able to perform that way. So, what one is supposed to have is that clean flow as best possible way is going to I mean is going to hit the turbine so that now if you zoom further what you see the obviously from firm's perspective the flow at later turbines is not fresh and won't contain as much as energy which I've been talking about the later turbine would not be able to produce the energy as you expected The primary reason behind that is that that is within the wake or the effect of this first turbine or second turbine. So, the third turbine, under the effect of these two, so, that's what it will be able to produce the power as much. And if you look at the individual perspective, so, wake limits the extractable power. So, that means in simple words, if this turbine there of similar kind if it exposed to clean air it can produce let's say p1 power then this would be p2 and this is p3 obviously p3 would be way less than p2 than p1 this is what is going to happen because p3 is having an impact of so but ideally what one would expect that E1 should be equivalent to P2 should be equivalent to P3 almost.

So, that is the ideal situation that all three of them, that's what the advantage of the farm, you would kind of, what you see, the wake is pretty big and some of the turbines are already sitting inside the factory. Now, the question comes, what is this wake doing? Okay. So, that's something you can see. So, obviously there will be some implications which is on lift. Angular momentum detour.

Some experiments that one can see. How does the wake affect wind turbine? Then conceptual way to model the wake, how we practically information to. So, that's how now coming back the airfoil that we have already seen that when the airfoil is within a fluid, when the flow passes over this, obviously you have lift and drag force, which is One is the normal to the flow. Other case is the perpendicular to the flow. So, that's what you get.

Then lift and drag force would allow you to. So, here is the one where flow is going around that. and then you have this flow coming then going out then there would be reaction force now if you see another perspective, so, this is the flow coming in remains attached here and then it goes around that so this is where you see, so, what it creates you get to see some kind of a circulation not rotation okay so you have some circulation around this particular error file, so, when the error file goes through this kind of an inside here this kind of a flow pattern so this generates some kind of a circulation, so, how do we estimate that you can estimate in a slightly i mean simple way let's say you say that the whole objective is at rest Then you impulsively start it. You raise the speed up to that point. Then you stop impulsively.

So, this is what it is. So, this is a velocity time curve kind of thing. Then for constant lift coefficient, what happens to lift? So, the same thing, if I have constant lift coefficient, then what happens to lift? I would have at rest, impulsively start impulsively stop, so, at the same way when i impulsively start a lift and that lift remains constant till i impulsively stop it, so, this is how you, so, then when you look at that airfoil structure around that circulation would be formed and how the circulation would be there So, when I start impulsively the circulation is going to be formed which is bound to that wing or the airfoil and then when I stop it comes down. And, what happens to that circulation that one has to have conservation of angular momentum. So, the angular momentum of the flow bound to the wing would also be generated.

So, what about the conservation of that? So, one has to because this is again something when you have and this angular momentum would come in picture because your body or the solid is rotating. Okay. So, that is there. So, now question here is that what part of the flow might be acting to conserve angular momentum. So, that is something we have to see.

Now, we go back and again see the same wake structure. So, the wake is a distributed flow. So, behind these obstacles, so, these are all weak that you see and these are highly turbulent in nature. So, what is there is a hypothesis which could be possibly that the weak acts to conserve angular momentum. That could be an hypothesis.

But yes, one has to showcase and establish that. So, now we can see how that can possibly happen. So, We have to see hypothetically how would that work. So ,we'll come back to this particular status of the situation. So, the speed, we have started impulsively.

Accordingly, you get a leap instantaneously generated. Then you have a circulation which is going to... So this is an aerofoil and it is exposed to a flow.

So, the flow goes around the aerofoil. So, obviously you have a circulation over there, which is gamma. and then the angular momentum of the flow bound to the wing. So, when I have the same situation, what happens is the angular momentum set into wake at start. As soon as I impulsively start, speed goes up, lift goes up, circulations start happening, angular momentum set into wake at start.

Then when I stop, then the angular momentum also said into the wake at stop so this is what we are trying to kind of swing where it is stopping yes some portion this is impulsively stop, so, when i impulsively start it's going then impulsively stop some portion is also can be a reverse one so that's where the then the circulation said into the wake also at sudden stop because obviously as soon as the flow is stopped or impulsively started flow is stopped that is also going to happen so now we can see by some observation that or measurement that how things happen and What happens to that? So, you have some 2D experiment, which is an impulsive start. We want to see, or we try to answer, is there anything said into it? So, that's the first question that we try to address. So, let's say it's an impulsively start. Is anything said into the way? So, we have started impulsively, and we want to see if something is shedding into the uric. So, once we do that, you can see the flow structure like that.

You see all this gap that we have done. And, you can start seeing some structure which is happening and then going. So, thing that you get to see, yes, there is something which is shedding into the wake. Now, that means if you see the sequence of structure, when you start the system, here is the situation when the flow remains there, it goes, now impulsively you start, then you start getting this kind of things, So you see this.

It goes here. It starts going like that. So, there is something which is happening. So, now the second question is that is circulation said into the week. We can see now we have some measurements where the particles are there. So, these are the circulation because flow is coming.

So, there is a circulation. So, you see the circulation pattern. Is the circulation setting into the week? now next picture it shows something is moving out so then you get another pattern which is going out so the point is that its circulation said into the wake the answer is yes, so, that means that here when you impulsively start this flow the circulation sets into the quick, so, that is there. Now, more you can look at from the infinite to finite wings. So, this is something where you have circulations.

These are circulations. Then this is an infinite wing. That means if you look at the finite wing, you can see this cross-sectional area. So, the leading edge, there is a circulation. And, obviously the lower face is always high pressure, upper face is low pressure. Then here you always, you can see at the tip, a trailing edge, there will be circulation.

So, which you can see that around the wing tips. So, both the infinite and finite wing shows some kind of a circulation around that. So, is the circulating motion trailing behind wingtips? Now we can look at that through some measurements. It's a 3D measurement, steady level flight. That's the circulation tail behind the wing.

You can see the structure, which is getting captured. And now next set, you pin this side. And this side, you can see, let's rotate this side. So, essentially what we are trying to do, we try to mimic the situation of the rotor blade and try to see what happens.

And this is what you are going to see. That one side if you pin, the other side if you rotate, then the circulating motion trailing along the helical path behind the rotating wind tips. So, same thing you get to see in the turbine. So, obviously we try to answer the circulation trail behind that. So, this picture clearly show the the circulation trail behind that. So, this is what it shows and it clearly states that there is another image where clearly shows that the circulation trail behind the wing tips.

So, and if you pin one end and allow the other end to rotate then obviously the circulation going to be there. So, that means  What is this wake doing? The wake is essentially conserving the angular momentum. So, that is what wake is doing. So, it's conserving the angular momentum. Now second question is what we would like to see.

So, wake does angular momentum conservation. Now, how does wake affect wind turbine? Now, we can see this particular experiments where the rotor blades are rotating in a tunnel and you see this boat structure and all these things. What happens? It is going to have some or have some velocity deficit. This is an uniform flow which comes towards the rotating rotor blade. And when it passes, then at the downstream, what you get to see, there is a profile like this.

So, you have some kind of an velocity deficit, or the weight actually decreases the velocity. So, if you see the velocity profile here, so, the uniform flow which is approaching to the turbine, and after turbine you get to see this,  So, the weight decreases the velocity. And this is going to impact your power output because power is proportional to velocity cube. So, once you have less velocity, then it is going to decrease your power as well. Now, the question that we have  How does the weight affect an airfoil? You take a simple airfoil and there is a circulation.

So, if you see this is effective velocity, this is apparent or apparent velocity and this is the induced velocity and there is an angle of attack alpha. So, this again bringing back to that particular, bringing back to that particular these things the velocity triangle principle and we can see, so, this is the airfoil where you have effective alpha in this velocity and if you put them in, so, this is my lift and drag and that's my resultant force, so, the this I mean purple one is due to the projected according to ue and the green one is projected according to ue so there is an slight difference of that and these differences are called drag induced lift via circulation, so, this difference is called and the other one, so, what that tells you that weight weight effectively increases the drag that means and that is quite natural in that sense that when you have weight that there is a velocity reduction and that velocity reduction is going to impact the power production and then you will have some effectively the drag increase okay now One conceptual way to model the wick is like we can imagine this following. So, simply we imagine that there is an invisible state which is called current conducted in a structure which is called wire. So, these are wire. Then the produces a force field which is electromagnetic field.

And then there is a circulation, certain particles, this is magnetic circulation. So, that's a correlation one can establish between this, what do you call, electric field and the flow field. So, what we could correlate, the current we could correlate with the vorticity. The way that we say that could be vortex.

The electromagnetic field could be pressure field. The magnetic things is the fluid. So, the analogy is also pretty similar. In the electromagnetism, you have Poisson equation for electrostatics. So, that includes your vector potential with the current density, Ampere's law. But, in aerodynamics, this is psi is the vector potential, omega is the vorticity.

And obviously, this is the definition of vorticity and flow field is E infinity plus del cross flow. So, once you define a circulation, as flux of vorticity through surfaces, then you get this. Now, if we extend that similar analogy between this electromagnetism and the aerodynamics, and the Kutta-Joukowsky expression says that the lift per unit span is proportional to circulation. So, you can get lift, which can be correlated with circulation and the fisting velocity, and you have that. So, you bring in that analogy, same analogy in the equation.

So, there you have the del square size minus omega, you have all these definitions. So, finally, the solution would be in format that you have infinity plus this integration. So, once somebody is able to do that, then you're able to find out that correlation. and then find out the solution, so, there is a nice correlation or kind of a connectivity one-to-one connectivity between the electromagnetic field and the aerodynamic field here, so now, you talk about the boundary layer, so, you have infinitely far away then you see this, so, there is a solid boundary then there will be 15 things So, this we have been kind of talking about that. So, if the boundary layer is that this is solid boundary and close to that you have no slip boundary condition and, up to certain height you have the shear gradient is strong beyond that the shear gradient is pretty much negligible.

So, if you look at the fluid particle here and the fluid particle here, they are having different kind of issues because here the viscous is related to the viscous here, but here it might be negligible from the solid bodies. So, what you can do, these boundary layer theories and all these things that we have already talked about, that can actually bring some nice situation here, so, you remember we are trying to solve this ux equals to u infinity plus this integration now, we can separate this v into two part one is within the boundary layer let's say we marked with the red omega and otherwise the external flow which is outside the boundary layer outside the boundary layer your viscous effects are negligible, so, the point here is that we are trying to kind of demark it in two component one is within the boundary layer where viscous effect are there and then outside boundary layer so in boundary layer external or x outside the boundary layer the body city is zero so that drops out from the integral, so, it is become ux is infinity within boundary layer that is not zero, so, local circulating motion of fluid element due to the specific state so these are potential flow example and things like that so what you can see this boundary layer concept actually saves a lot of effort so here you see there is a boundary layer here and outside that boundary layer there is no effect okay so what we can do we just break that into two component in the whole domain and then try to segregate out so this is precisely what you do you see the boundary layer formation and then try to mark them so this is outside boundary layer and this is within boundary layer so, this red shows that within boundary layer this has to be integrated and this is outside boundary layer so, the whole solution would be in two component u infinity plus the boundary layer component which is required the non and the outside boundary layer component so, that way if, you segregate that out that actually gives you an easy solution and so, it discretize omega into vortices and then points curves and lines surface integral so, finally you get the solution of the elastic field so, what it gives you that once you outside the body and inside the body you segregate that out within boundary layer and outside boundary layer then it is easy to find out the solution and that is what it is doing so what we talked about is that the wake so wake conserves angular momentum but at the same time wake decreases the velocity and now because of that you get some induced drag and all these things so that is something one has to take into consideration while designing this thing okay so with that we'll talk about other thing in the next session thank you