Wind Energy

Prof. Ashoke De

Department of Aerospace Engineering, IIT Kanpur

Lecture 58: Control and miscellaneous aspects of wind turbines

Welcome back. So, what we'll now continue because we have talked about now the dynamics and mechanics and then simplified linearized model to analyze the design procedure. Now what we would important thing to note here is that the whole turbine unit is essentially responds to those different kinds of loads, whether it's a static or dynamic or those kinds of loads do arise during operation. So, what one has to do either It's a clear example of a coupled irrealistic problem or fluid structure interaction problem. So, one way to look at the complete design is that these days, the numerical techniques are quite evolved. I mean, later on, we'll quickly touch about the CFD part of it.

So, one can use complete numerical approach. where you can have that whole geometry can be totally solved through simulations, which could be fluid simulation alone, which is a CFD simulation. Then you can get all the aerodynamic forces and then you can pass those forces to the structural solution and find out the structural responses. there are standalone ways so so the, for flow simulation one can use completely cfd then from here you estimate all loads then you can do structural analysis and find out the solution which can be used for the design purposes.

Now, this alternate, this is more like an applying numerical tool. So, alternative to that, that we have discussed in details, the linearized simplified model, which is essentially the full mapping equation models, incorporating different interacting effects and components. So, one can use those simplified models, which are quite handy to get you initial design data. then once you get the initial design data then you can apply your numerical tools and then get complete picture or complete analysis of it then go for final fabrications and prototype testing now regarding that complete uh cfd or full simulation of the flow simulations or aerodynamic simulation but we'll talk about the cfd and all this later on now Coming to the structural analysis, there are, I mean, different ways to get the structural response. So, I mean, already you can see that, I mean, wind turbines are complex structure.

So it is necessary to determine various aspects of the response such as stresses within that structure, deflection, natural frequency. Obviously, you can use mathematical model to find out that there are also mathematical relations that can be used to describe the behavior of those real system. Models can vary widely depending on the complexity incorporated in that physical model. Typical application for mechanical models in wind turbine design use simple model for control then model which is sufficient for illustration then you can have detail model for investigating static deflection response then model for determining natural frequency of component or complete system. So, like the linearized Hinge-spring model that or Hinge-spring dynamic model that we have discussed that can be useful for elucidating the first order response of wind turbine rotor to a range of input condition.

However, it is not that extremely useful in those situations where the important aspect of the response would not become apparent using the such simplified. So obviously, these are simplified situation. So, to overcome that kind of situation, one has to use some specialized nonlinear models to investigate the dynamics of the complete turbine system, such as tip flaps, blades, pitch linkage gear trains. So, yes, I mean, single simplified model cannot do that kind of analysis. And that is what we are talking about numerical tool or complete numerical tool, which can be handy to estimate the complete picture of the system.

So, one can do slightly segregated ways like you do the load calculations or wind load calculations or aerodynamic load calculation through CFD and then use those loads for the structural responses. or can have a coupled system, complete aeroelastic behavior, but which is really, really complicated. Even with the numerical powers, computational resources that we have today, still it's quite challenging for complete turbine system to have it. But component-wise, yes, it can be done. And probably it would be good idea to look at that.

So, when I come to the structural response. So, there are I mean structural analysis can be done using different ways. I mean the best way to do that using complete finite element method. So, that means you will have the whole geometries and greeting and then run those finite element for structural responses and things like that. Or one can use lumped parameter method.

Okay. So, in lumped parameter is one in which a non-uniform body is considered to be made of a relatively small number of bodies which can be simply characterized. So, this characterization may consist of as little as the mass of the body or it may include other parameters as well such as thickness. For example, the drivetrain of a wind turbine in reality consists consists of a number of rotating components such as rotor itself, shaft, gear, generator rotor. So, in modeling a drive train, it is common to characterize as a few lumped inertia and stiffness. So, that means you can kind of consider different components and use their stiffness or inertia as a lump parameter and use that in a simplified analysis.

So, that is obviously cost effective compared to finite element method, but it is better than simplified linearized system. Now, we can have modal analysis. So, modal analysis, again, is a method which is used to solve the equation of motion in multiple degrees of freedom vibrating system. So, this particular approach allows coupled equation of motion to be transformed into an uncoupled modal equation, which can be solved separately then. And then finally, the solution from each modal equations can be superimposed or superpositioned to give the complete result.

So, this is quite useful for linear systems with classical damping. Or, one can use multi-body analysis. So, in multi-body analysis, it is the modeling approach of the motion of a mechanical system that comprises more than one component, where bodies are distinguishable subdivisions of the larger structure that are relatively uniform with each other. I mean, for example, a wind turbine includes tapered or twisted beams. Various other tapered parts, couplings, and generator gears.

The bodies may move in a variety of ways with respect to one another. Bodies can be rigid or flexible. Bodies are joined together by links that may incorporate certain constants. So, the multi-body method involves the creation of dynamical equations involving the various bodies at their constants. So, this is an involved analysis, which is done in classical mechanics, which is an extended version of Newton's law of motion.

But it has become progressively more complex and inclusive over time. Okay, so this multibody analysis is quite popular. I mean, obviously, if you see that, either you can have a linearized system or a simple linearized model to carry out the analysis, or you can have something slightly more complicated, like a lumped parameter method where you couple together different components, for example, all of them and consider them as one big unit. Unit and having some inertia and stiffness, and all this, you can solve that you can do modal analysis, which is multi-degrees of freedom vibration analysis, and then finally, once you get those modes, you can kind of add them together to get the final solution. You can do multi-body analysis, and FM is the kind of the, so this is where you get the structural analysis.

And for wind loads and all these, you can use the complete CFD or a coupled aeroelastic problem using CFD and a structural system. Now, just quickly touching upon it, there are also electrical aspects of wind turbines. For example, the electricity is essentially generated from the wind turbines. So, the electrical aspect is also very important. I mean, there are different components and electrical issues that are significant in the wind energy system.

Like, you have power generation. So, those are generators for electric conversion. Then you have interconnections and distribution. We have power cables. Switch gears, circuit breakers, transformers, and power quality; then you have control over sensors, controllers, yaw or pitch motors, and solenoids.

Then you have site monitoring, data measurement, and recording. Data analysis, storage where you need batteries, rectifiers, inverters, and lightning protection. You have grounding, lightning rods, a path, and then you have loads, which include lighting, heating, and motors. Okay. So, these are the, I mean, obviously, yeah, these different aspects of the electrical system, like power generation, interconnections, control site monitoring, storage, and lighting protection.

So, I mean, one also has to look at it. I mean, truly speaking, this whole wind energy system design integration is a multi-disciplinary system; it requires not only an understanding of aerodynamic forces and their sequences, but also structural responses. Additionally, you need a basic concept of electrical power, power transformers, electrical machines, power converters, variable speed wind turbines, and other components. ancillary auxiliary systems which are associated with that, so, one has to have a quite clarity about this aspect of it as well similarly, i mean, this is one aspect of the now so, electrical side of it that one has to know similarly, one has to understand the Wind turbine materials and components can experience material fatigue due to dynamic loading, so the materials typically used in wind turbines are varied. For example, if you look at the blades, these are composite materials, specifically subcategories such as carbon fibers and wood laminates.

Polyester resins, epoxy, then hub; you have steel, then gearbox; you have steel, where you can have various alloys; lubricants, then you have generator: steel, copper, which is rare earth-based permanent magnets; then mechanical equipment, which is again still; then you have nacelle cover; it could be composites like fiberglass. Then you have a tower, which can use steel. Then you have a foundation, which could be steel or concrete. Then you have electrical control systems, all of which would be copper and silicon. So, you can see there are different materials that are often used in the different components of this.

Also, you have different machine elements such as SAP, couplings, bearings, and unit gears. All these are the different kinds of gears and gear loading. All these can also be estimated. Then you have principal wind turbine components, which are the rotor, so the rotor will include blades, aerodynamic control surfaces, and the hub. Then, the blade design considerations must take into account aerodynamic concepts, aerodynamics performance, and structural strength.

Obviously, that's how you do the design and finally get the blade shapes and all these things. You find out the blade, I mean, the number of blades, airfoil, solidity, and all these things. Then, obviously overall system structure stability and those things are there. Now, I mean, wind turbine. Essentially, the design procedure includes all of this, okay.

So, one has to determine the application, review the whole design procedure, determine the application, review previous experience, select topology, estimate primary loads, develop tentative design performance, evaluate design, estimate cost, refine design, build prototype, test prototype, and do that. So, all of these are part of the wind turbine design procedure. Then you have the turbine topologies that one has to find out, technical specs, certification; you have to calculate the wind turbine loads, load scaling relations, power curve predictions; then obviously one can have, I mean, computational code to estimate all these. Then finally, you have design evaluation, where you can prepare the wind input model and the turbine performance simulation to obtain loads.

And assess the damage. So, with a wind turbine, one can do component testing, and all these things can be done. So, after doing the turbine component testing, one now has to understand the control of the wind turbine. So, what we have in the control is you have passive control by mechanical design. So, in passive control, you make this kind of modification to the geometry, or you can have active control by using a sensor-actuator system, where you have a digital controller or amplifier, actuator, turbine, and sensor, and use those to control the system. So, when you look at the sensor, sensors are used in different components to sense the generator speed, rotor speed, wind speed, UR rate, temperature of the gearbox oil, generator winding, ambient air, blade pitch, blade azimuth, U-angle, grid power, current voltage, grid frequency, top acceleration, gearbox vibration, and subtot, and the environment, whether I see humidity and all these things.

So now, there are actuators, which are generators, motors that control pitch and yaw, linear rotors, magnetic switches, hydraulic power and pistons, resistance heaters, hands, brakes, and all these things. Now, how the control architecture looks is that you have a wind farm operator; you start up, then online control component-wise, then shut down.

So basically, dynamic component controllers handle emergency shutdown and fault monitoring, and soon they come back. Usually, supervisory control is at a high level for turbine status appearance, while dynamic control operates at a low level, so dynamic control. is low-level, and that is, for example, torque, pitch, power, etc.

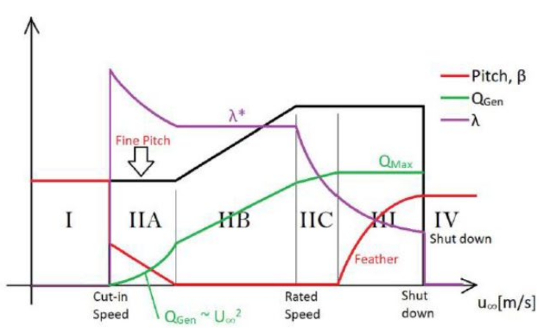
And supervisory control is on. High level for turbine operating status. Now how do we control a variable speed turbine? Actually, we have a main actuator for speed control that is a blade pitch and generator torque. Here is the rotation speed as a function of wind speed, and it is broken down into different segments. Cut-in speed, rated speed, sudden speed, and rated arc. So, with the problems that the wind speed on the rotor disc cannot be perfectly known, what are the maximum power production and power coefficient that can be? obtained.

So, we have power, which is basically area times free stream velocity times coefficient of power. So, these are the tip switch ratio, collective base pitch, and all this we have known, and then what we can find out is that Q generation in the generator torque is in equilibrium with the aerodynamic region 2a, where lambda is fixed, beta is maximized, and cp could be a function of this. In region 2b, which is subrated, lambda is lambda star, beta is beta star, and cp is cp star. In regions 2c and 3, lambda is again fixed, and beta regulates power at maximum power, so this is how you can get some kind of an.

$$P = \frac{1}{2}\rho A \cdot {u_\infty}^3 \cdot C_P(\lambda, \beta)$$

$\lambda = \Omega R / u_\infty$ is the tip speed ratio
B = the collective blade pitch
Cp = power coefficient, maximized at $\lambda = \lambda^*$ (e.g. = 7) and $\beta = \beta^* = 0$ ($Cp^* = Cp(\lambda^*, \beta^*)$)
(Note: $*$ means the optimal value)

Q_{Gen} is the generator torque. In equilibrium, $Q_{Gen} = Q_{Aero}$



Pitch, torque, λ V.S. wind speed

- Region IIA: λ is fixed to $\lambda_{\text{fix}}^{IIA} = \frac{\Omega_{\min} \cdot R}{u_\infty}$ and β is maximized.

  $C_P = C_P(\lambda_{\text{fix}}^{IIA}, \beta)$

- Region IIB (subrated): $\lambda = \lambda^*$ and $\beta = \beta^*$

  $C_P = C_P^* = C_P(\lambda^*, \beta^*)$

- Region IIC & III: λ is again fixed to $\lambda_{\text{fix}}^{IIC} = \frac{\Omega_{\max} \cdot R}{u_\infty}$ and β regulates power.

(Region III is at maximum power.)

Torque $Q_{\text{Generator}}$ can be controlled directly and should counteract aerodynamic torque Q_{Aero}. Given rotor inertia I we have the ODE for Ω:

$$I\dot{\Omega} = Q_{\text{Aero}} - Q_{\text{Generator}}$$

Q_{Aero} depends on u_∞ & Ω & β and is given by $P_{\text{Aero}} = \Omega \cdot Q_{\text{Aero}}$, where $\Omega = \frac{\lambda}{R}u_\infty$ so that $\lambda = \frac{R\Omega}{u_\infty}$:

$$\begin{aligned}
Q_{\text{Aero}} &= \frac{P_{\text{Aero}}}{\Omega} \\
&= \frac{1}{2}\rho(\pi R^2){u_\infty}^3 \cdot \frac{C_P(\lambda,\beta)\cdot R}{\lambda u_\infty} \\
&= \frac{1}{2}\rho\pi R^3 {u_\infty}^2 \underbrace{\left[\frac{C_P(\lambda,\beta)}{\lambda}\right]}_{:= C_Q(\lambda,\beta)} \\
&= \underbrace{\frac{1}{2}\rho\pi R^3 {u_\infty}^2 C_Q(\frac{\Omega R}{u_\infty},\beta)}_{Q_{\text{Aero}}(\Omega, u_\infty, \beta)} \\
&= \frac{1}{2}\rho\pi R^5 \Omega^2 \left[\frac{C_P(\lambda,\beta)}{\lambda^3}\right]
\end{aligned}$$

How to choose $Q_{\text{Generator}}$ when only Ω is measured?

Idea: Find the function $Q_{\text{Generator}}(\Omega)$ that brings turbine to an optimal tip speed ratio λ^* (in region IIB)). Intuitively, setting high Q_{Gen} if Ω is too large and small Q_{Gen} if Ω is too small in order to stabilize the rotor speed. At optimal $\Omega^* = \frac{\lambda^* \cdot u_\infty}{R}$ we would have:

$$Q_{\text{Aero}}(\Omega^*, u_\infty, \beta^*) = Q_{\text{Gen}}(\Omega^*)$$

So let us generally try the law:

$$Q_{\text{Gen}}(\Omega) := Q_{\text{Aero}}(\Omega, \frac{R\Omega}{\lambda^*}, \beta^*)$$

$$= \frac{1}{2}\rho\pi R^3 \left(\frac{R\Omega}{\lambda^*}\right)^2 \frac{C_P(\lambda^*, \beta^*)}{\lambda^*}$$

$$= \underbrace{\frac{1}{2}\rho\pi R^5 \frac{C_P(\lambda^*, \beta^*)}{(\lambda^*)^3}}_{\text{constant } K_{\text{Gen}}} \cdot \Omega^2$$

control. Now, when we talk, the Q generator can be controlled directly and should account for aerodynamic torque when we know the given inertia. So, aerodynamic, I mean the torque is the power of aerodynamic power divided by the rotational speed. So, if you put this expression back, you can find out how to choose the q generator when only omega is major. The idea is to find the function of the q generator that brings the turbine to an optimal peak speed ratio by intuitively setting the q generator, and then we can use the basic equation to find out how one can do that. Control this whole system like that, so apart from the control aspect, there are other things, like, uh, energy application.

Okay, so that means one can look at the distributed generation hybrid power system, offshore wind energy. So, those are here. Then, one has to look at the economics of wind energy systems. So, that is another important part because it's not only the design and operation of the system; economics is another aspect one has to look at. And also, one has to look at the wind energy where environmental aspects and impacts are concerned.

So that is another thing. So, not only the design of a system, but also looking at its environmental impact and aspects must be considered. So, when you try to design the complete system, one would like to have a complete picture of the overall system, starting from site selection to the design procedure and its subsequent impact. to be in place. So, these are the different aspects that one has to take into consideration in the application of wind energy. Now we'll talk about some CFD aspects and alternative concepts.