Mathematical Analysis of Wind Turbine Blade at various Angle of attack and Reynold Number

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Abstract
This work utilizes only the closure system k-ω SST RANS to model wake growth and resolution for both a single fully resolved rotating turbine and two fully resolved rotating turbines in-line. These simulations have been effective in predicting wake growth and resolutions, as well as predicting downstream turbine speed deficits. The precise wake structure and helical tendencies also showed. The findings of vorticity also showed a precise structure of the wake and helical tendencies. Results clearly shows the variation of C_l and C_d with angle of attack. Thus, for a particular Reynold number the optimum angle of attack came between 350 and 400. With the increase in the Reynold number C_l also increases, and wind turbine efficiency increases by 20%.

1. Introduction
The design and evaluation of rotors focuses mainly on maximizing the energy coefficient according to the tip-speed ratio. The tip-speed ratio is the relationship between blade tip-speed and incoming wind speed. This ratio is also directly related to solidity, which reduces the cost of power generation. As a result, a longer blade produces a greater tip-speed ratio and a higher the rotational speed.

For a long time, the question of what turbine size generates energy at minimum price has been discussed. Large machinery speakers support economies of scale and enhanced wind speed [6]. Opponents of this camp think in the ‘square-cube’ law, which improves energy consumption with a diameter square while the mass of the rotor rises with the cube and thus controls the cost. In reality, both statements are correct and the effects of wind shear are taken into account by the trade-off between scale economies and a variant of square-cube legislation. Using easy cost modeling, this trade-off can be examined, but this will not be regarded in this thesis. You can find more data on this topic in the Wind Energy Handbook [8].

Because high winds can cause damage to wind turbines, they need to be designed with aerodynamic controls to maintain power. These controls include stall control, variable pitch control and yaw control. Stall control alters the wind’s angle of attack on the blades of the rotor. Variable pitch control is accomplished by changing the angle of the blades along their long axis. This decreases the lift force available to turn the rotor and allows for more control than a stall control. Variable pitch control requires a more complicated hub assembly in order to have the desired mechanical control. As a variation on the full blade pitch control, there are some designs that have an option for partial span pitch control. By turning the rotor away from the dominant wind direction, Yaw control achieves aerodynamic energy control. This technique needs a very solid, torque-enhancing yaw control scheme.

The Blade Element Momentum (BEM) model is the most fundamental method for wind turbine analysis. Originally developed by Glauert in 1935 for analysis of airplane propellers, it is a one-dimensional approach that models thrust as a function of wind speed. The principal function of the
BEM model is to determine the conditions for maximum energy conversion (Leishman et al. [10]). The most elementary models, as described by Leishman et al. [10], for predicting the neutral boundary layer are the power law and the logarithmic law. It should be noted that these methods only produce reasonable predictions for perfectly neutral ABL flow. The power law states:

\[
V_\infty(h) = V_\infty(h_{ref}) \left( \frac{\ln h}{\ln h_{ref}} \right) \frac{\ln h_{ref}}{\ln h} \frac{1}{\kappa}
\]

Montavon et al. [11] performed another example of the use of \( k-\varepsilon \) RANS turbulence closure. In this study, a finite volume commercial CFD code, FLOW-3D, was utilized to model neutral and stratified flows over complex terrain. To achieve a model capable of handling stratified flows the conservation equation and buoyancy term was implemented with potential temperature.

Empirical models, like the BEM technique, the growth of the wind energy sector has played a significant part. However, as the sector continues to develop and prime farm sites become scarcer, leading in greater density turbine positioning, sophisticated CFD simulations will be necessary to satisfy demand and promote the sector. (Bazilevs, et al. [12]). A variety of techniques and methods have been used to study wind turbine wake interactions (Hahm et al., [13]; Porté-Agel, et al. [14], atmospheric wind farm effects (Calaf, et al., [15]; Meyers [16], and structural loads and spacing (Bazilevs, et al.; Meyers et al.). These studies range from using RANS turbulence closures (Hahm et al.; Tachos, et al.), to LES with a variety of SGS models (Bazilevs, et al.; Calaf, et al.; Meyers et. Al [16]; Porté-Agel, et al., to a case using the vorticity transport model (VTM).

2. Model description

A system of discretization includes breaking down a geometry into smaller components like components, nodes or volumes. The resulting discrete geometry is called a grid or mesh, which is now a set of several smaller computational areas. Simulations precision generally improves with a growing number of cells, i.e. declining cell size. But a certain mesh size compromise is virtual-ly always inevitable because of restrictions imposed by improved computer storage and runtime. Fluent-Mesh produces forms of linear tetrahedron, hexa-hedron and element wedge/prism. SST \( k-\omega \) CFD simulation model imposes a completely turbulent flow while XFOIL’s viscous boundary layer module accounts for a turbulent shift from laminar to laminar. These tiny separation bubbles, however, have a negligible impact on the airfoil speed field.
All simulations consist of two parts, one tunnel “stator”, and curved out blade “rotor”.

The various interfaces between the stator and rotor areas have been identified (Table 1).
### Table 1. Various stator and rotor interfaces

| Face | Domain Interface          |
|------|---------------------------|
| a    | Velocity inlet            |
| b, c, d, e, f, g, h, i    | General Connection        |
| j    | Pressure outlet           |
| k, l, m, n                 | Rotational Periodicity    |
| o, p, q                     | General Connection        |

In all nine areas, domain k and l cover half the entire bottom of the stator. The rotational frequency implies anything from domain k enters domain l. This enables the domain to be halved and many nodes to be saved in the mesh.

### 3. Results and Discussion

Simulations of wind turbine blade done for a particular Reynold number for different angle of attack like 50, 150, 250, 350, 450, 550, 650, 750, 850. Likewise, six set of simulation done for different Reynold numbers like 12500, 250000 and 6000000. Reynolds number 6000000 correspond to 12 m/s wind velocity, which is the optimum speed for GE’s 1.5xle wind turbine model.
Fig. 4 Graphical depiction for Re=12500 a) AOA vs $C_d$ b) AOA vs $C_l$

Fig. 5 Graphical depiction for Re=250000 a) AOA vs $C_d$ b) AOA vs $C_l$

Fig. 6 Graphical depiction for Re=6000000 a) AOA vs $C_d$ b) AOA vs $C_l$
From fig 4 (b), fig 5 (b), and fig 6 (b), we can infer that optimum angle of attack is 35°. Lift coefficient is maximum at this angle, power coefficient is higher. Although the distinctions between the theoretical and the CFD-based values are minimal in the upstream part of the process, there are significant downstream part variations owing to the wake region's distortion of the flow.

4. Conclusion
Dynamic analysis wind turbine blade with medium speed is conducted in this work. This investigation is based upon the beam finite element modeling of the blade. Power coefficient varies significantly with AOA distribution over the wind blade. With favorable AOA we can maximize the lift coefficient and drag coefficient minimize. Following conclusion is made from this study.

- We found that result of analysis for C_l shows some deviation with experimental results for lower value of angle of attack. However, the greater angle of attack indicates close match with experimental values.
- In general, we can conclude that with increase of Reynold number, lift forces and drag forces increases. Both CFD and experimental results indicates that, GE’s 1.5xle gave more lift coefficient at higher Reynold number.
- From the result the optimize angle of attack comes out 35° from the simulation.

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