Modeling the EOLOS 2.5 MW Wind Turbine at Laboratory Scale with Accurate Wake Behavior

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Abstract

A wind tunnel scale model of the EOLOS 2.5 MW wind turbine was created with blades designed to mimic the complex wake behavior seen in field scale particle image velocimetry behind the turbine by attempting to match the tip-speed ratio and power coefficient. Numerical simulations were run on the model to determine power coefficient and to map the flow of the wake behind the turbine.

Background

Research pertaining to horizontal axis wind turbines has reached such a mature state that the most promising avenues for efficiency improvement seem to be through study of the correlation of wind turbine wake behavior with incoming wind turbulence thereby potentially developing advanced control mechanisms that improve efficiency. Advanced wind energy research facilities, such as the 2.5 MW wind turbine available at the University of Minnesota EOLOS field site at UMore Park in Rosemount, allow for precise measurements of wind conditions, turbine performance characteristics, and blade deformation behavior. Using these facilities, prior work by Dr. Jiarong Hong's group has resulted the first ever particle image velocimetry (PIV) visualization of complex turbulent flows around a utility-scale wind turbine[1]. Using snowflakes as tracer particles, this data has allowed unparalleled imaging of wake behavior behind the EOLOS 2.5 MW research turbine as shown in Figure 1.

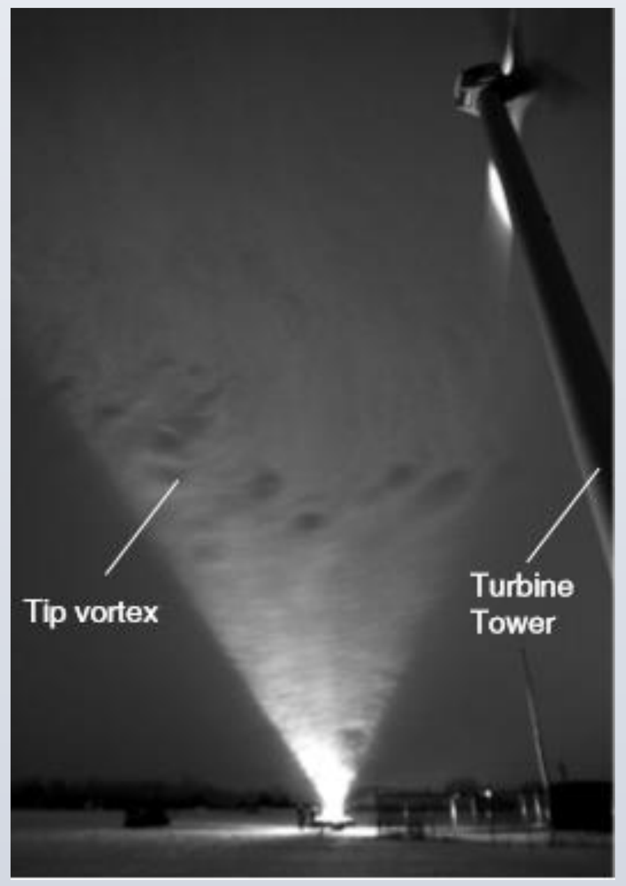

Figure 1: The set up used in super-large scale PIV

Reprinted from *Natural snowfall reveals large-scale flow structures in the wake of a 2.5-MW wind turbine*, by Hong et al., June 24th, 2014

Objective

The objective of this project was to create a laboratory-scale model of the EOLOS 2.5 MW wind turbine examined by Hong which produces similar wake behavior to that detailed by the group through PIV, a sample of which is shown in Figure 2.

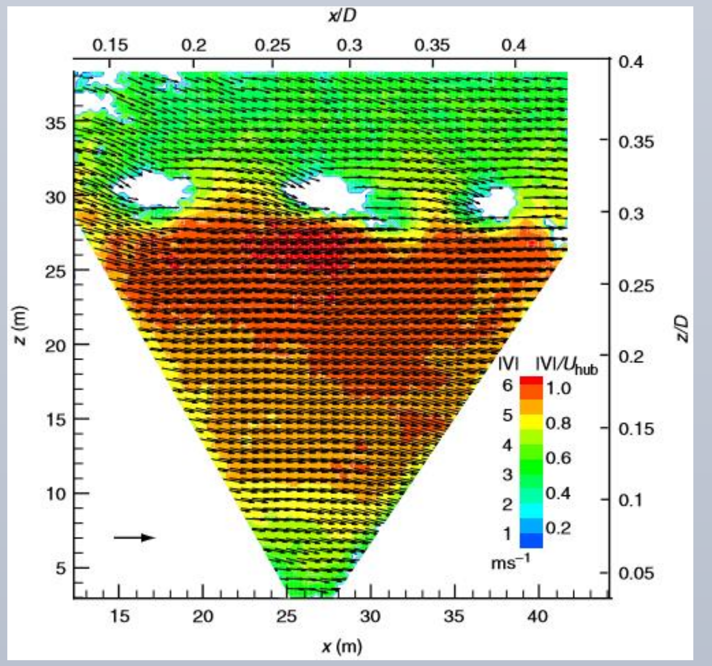

Figure 2: A sample velocity vector field from PIV data

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The model would undergo PIV testing in the St. Anthony Falls Laboratory (SAFL) wind tunnel to capture wake behavior for comparison with the full scale turbine. Such a model would provide a valuable analysis tool which can be easily manipulated and tested under various conditions in the SAFL wind tunnel to simulate effects on the 2.5 MW turbine.

Designing the Model

Literature review verified that the most important parameters to match for similar performance when scaling down a horizontal axis wind turbine are the tip-speed ratio[2] (TSR) and the power coefficient[3]. As power coefficient is directly correlated to the lift coefficient of the blade, the blades needed to be designed so as to match the lift coefficient of the EOLOS turbine blades. Since the achievable Reynolds numbers in the wind tunnel are much smaller than in those seen in the field, the blade had to be specifically redesigned at each span wise section to produce the lift seen by the corresponding section of the field scale blade. An example of the optimization is shown in Figure 3.

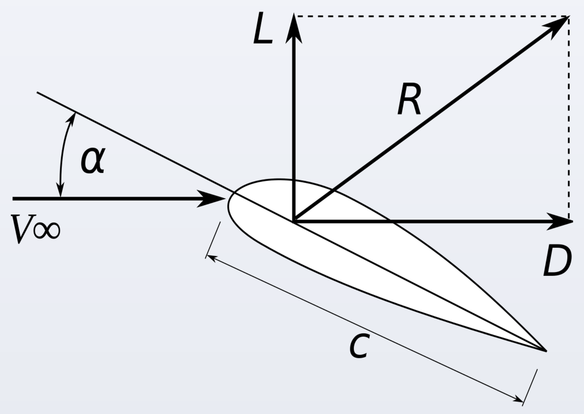

Figure 2: Aerodynamic forces on an airfoil

Source: Mónica Zamora. Wikimedia Commons

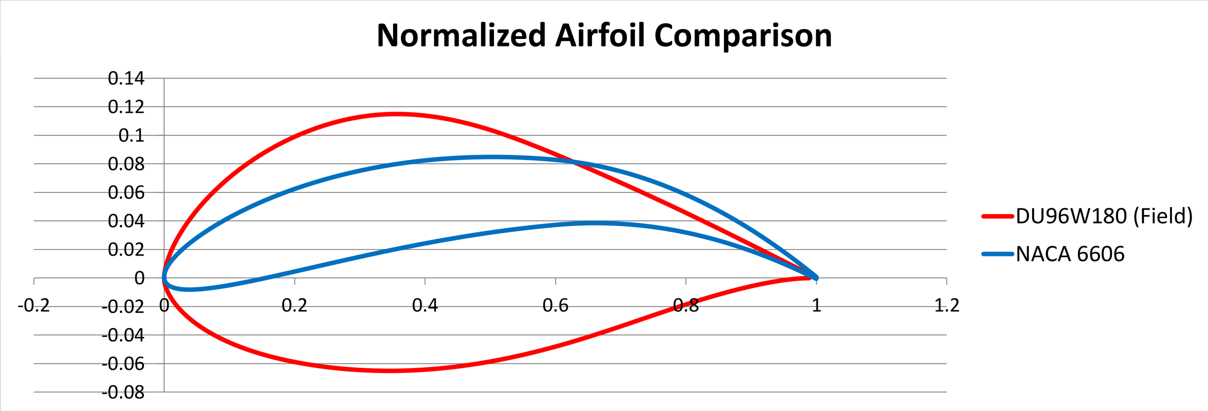

Figure 3: Example of a cross section redesigned to match lift of the field scale

Using field data from an April 2014 deployment by Hong's group and knowing that TSR had to be matched, Reynolds number and the optimal angle of attack were calculated. In addition, the overall chord length was tripled both for greater integrity of the blades and to produce larger tip vortices, a correlation found by Vermeer et al[4]. The 2-D airfoil analysis software XFoil was used to calculate lift coefficient of each blade section as shown by Chamorro[5]. The airfoil profiles were optimized at each of 18 span wise sections along the blade to match the lift coefficients of the EOLOS turbine. Using the optimized airfoil sections, a 3-D model of the model blade was created in SolidWorks and a full rotor was created by replicating the blade twice more around a geometrically scaled hub. Both models are shown in Figure 4.

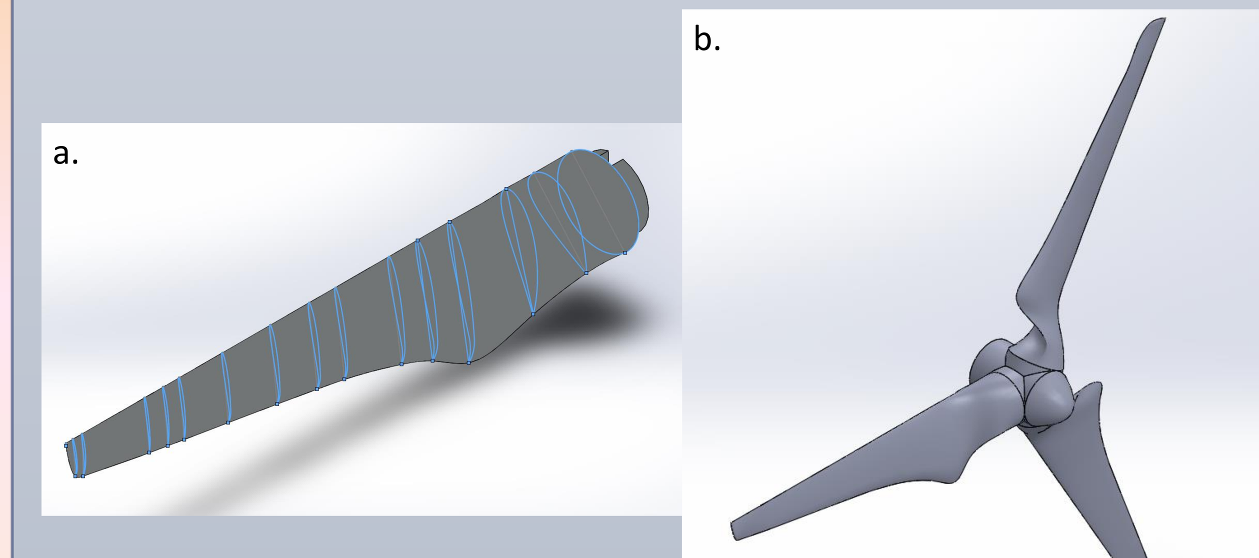

Figure 4: a) The blade optimized at each section, b) The full turbine with a geometrically scaled hub

This rotor was simulated to run at design conditions in the CFD software ANSYS-Fluent. The rotor was 3-D printed from three different printers with varying degrees of cost and precision. The most detailed of the three was selected as having the best chance of producing wake structures seen in the full-scale. In addition, a geometrically scaled tower shell was printed to encase the support rod and create a more realistic tower wake for PIV analysis.

Figure 5: The 3-D printed model.

Note that due to size constraints, only 2 blades could be printed on the rotor, the third was attached with adhesive.

Results and Analysis

Using numerical analysis, the vorticity profile of flow around the blade was mapped. Figure 6 shows a sample plot of time averaged vorticity of air behind the blade which indicates a area of relatively strong vorticity at the tip section, corresponding to the tip vortices shown by Hong[1]. Ideally, the smaller regions of vorticity closer to the hub not be present as they indicate small inconsistencies in the flow around the blade, however the main tip vortex region seems to be dominant.

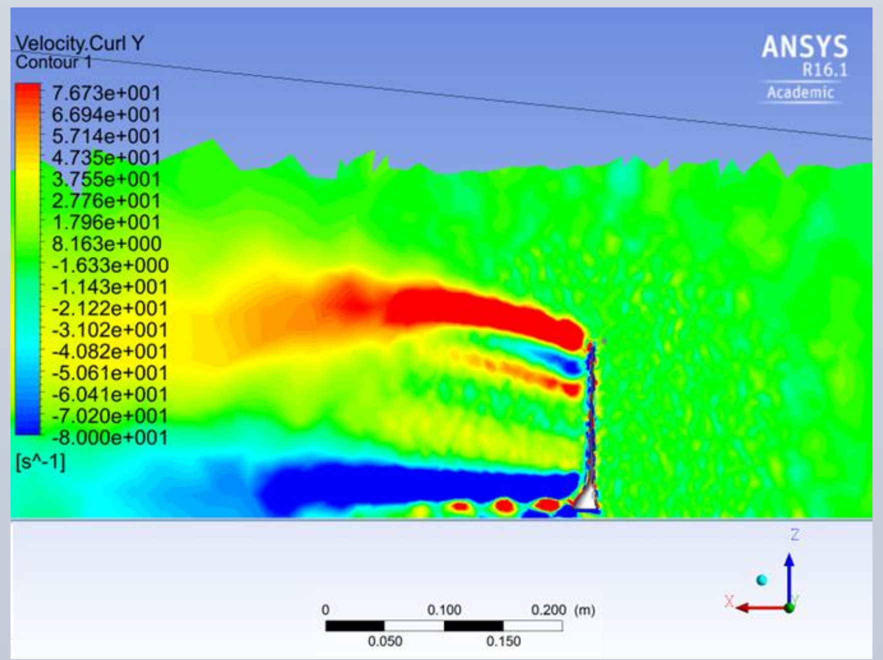

Figure 6: Time averaged vorticity profile of the blade indicating tip vortex behavior

In addition to visual analysis of flow behavior, the power coefficient of the model was assessed by the CFD software. The results of the analysis for varying numbers of grid elements resulted in differences from the field scale turbine power coefficient of 0.35 smaller than 15%. The resulting power coefficients for each number of elements examined can be found in Table 1.

Simulation	C_p
400,000 elements	0.36231
900,000 elements	0.3575
1,800,000 elements	0.3967
Field Scale	0.35

Table 1: Power coefficient from numerical analysis with varying levels of analysis precision

Conclusions

Using data and PIV analysis by Hong, a wind tunnel scale model of the 2.5 MW EOLOS wind turbine was created and 3-D printed. Numerical analysis on the model resulted in power coefficients within 15% of the field scale value of 0.35 and allowed the flow around the turbine to be mapped. Analysis of the wake showed expected tip vortex behavior. Future work will include using experimental PIV on the printed turbine model in the SAFL wind tunnel to confirm the numerical data and improving the model by optimizing a greater number of sections, including drag in optimization analysis, and including boundary layer effects when redesigning the model.

References

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