Wind Turbine Blade Design for Subscale Testing

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Abstract. Two different inverse design approaches are proposed for developing wind turbine blades for sub-scale wake testing. In the first approach, dimensionless circulation is matched for full scale and sub-scale wind turbine blades for equal shed vorticity in the wake. In the second approach, the normalized normal and tangential force distributions are matched for large scale and small scale wind turbine blades, as these forces determine the wake dynamics and stability. The two approaches are applied for the same target full scale turbine blade, and the shape of the blades are compared. The results show that the two approaches have been successfully implemented, and the designed blades are able to produce the target circulation and target normal and tangential force distributions.

1. Introduction

Turbine wake interactions affect wind turbine performance and the lifetime of the blades. For improved wind farm performance, a better understanding of wake behavior is thus necessary. Many of the details regarding wind turbine wakes are still not fully understood, since detailed experimental wake studies, especially reasonable size turbines with no blockage and scaling issues, are rare. Such experiments are necessary to allow for better understanding of wake behavior and to provide a means for validating computational models. Model validation, using a range of experimental data from wind tunnel test to data from full-scale operational wind plants, is critical for evaluating the capabilities of these models [1–3]. Validated models can be used for purposes such as improving wind plant layout and extracting more power with decreased cost from a wind farm.

A number of experimental studies have been carried out to understand and to predict turbine wakes better [4–8]. A comprehensive review on wind turbine wake research is given by Vermeer et al. [9]. Experimental wind turbine wake studies mainly consist of field measurements, wind tunnel tests, and sub-scale field studies. Field measurements are considered an important tool for characterizing full-scale wind turbine wakes as they experience real-world conditions. Different remote sensing techniques such as LiDAR can be applied to measure wakes produced by full scale turbines [4,5]. A great challenge for field measurements is the variability of the atmospheric conditions that prevents a full understanding of the collected data. Wind tunnel investigations present the advantage of repeatability with experiments being carried out under controlled test conditions [6–8]. However, many wind turbine wind tunnel experiments have been conducted using geometrically scaled down wind turbines. As a result, the wake produced by the model is likely to suffer from scale effects [9] and thereby misses some of the important physics present in
their full-scale counterparts. Sub-scale field studies have been developed to test wind turbines with better accuracy and lower cost, but with wakes relevant to full scale turbines. At Sandia National Laboratories’ SWiFT testing facility, multiple sub-scale (225 kW) wind turbines are being used to measure how wind turbine wakes interact with one another in a wind farm.

The overall goal of sub-scale testing is to test a wake with physics relevant to full-scale turbines, but at smaller scales where the measurements can be made under controlled conditions at lower cost. Critical to the success of this approach is designing wind turbine blades that produce wakes that contain the important physical features associated with full scale wind turbines. The objective of the current work is to demonstrate methodologies for the design of such blades and to contrast the resulting designs. Two different approaches for inverse blade design are presented in this work: 1) circulation matching designs, and 2) normal and tangential force distribution matching designs.

The circulation design methodology uses dimensionless circulation and tip-speed-ratio as the parameters to match for scaled wind turbine design with a scaled wake [10]. The circulation design is based on the governing equations of free-wake, vortex codes. The spatial and temporal rates of change of circulation determine the strengths and locations of shed vortex structures in the wind turbine wake. The second methodology is based on matching the radial distributions of the normalized normal and tangential forces for full-scale and sub-scale wind turbines. The wake develops from the interaction of the flow with the blade, which imparts a momentum deficit and rotation to the flow due to the forces/torque imparted by the blade on the flow. In addition, the wake dynamics and stability are affected by the load distribution across the blade [11]. Thus, it is expected that matching normalized force distributions should result in similar wake structure. In this approach, an inverse design method based on Blade Element Momentum (BEM) theory is applied. The two approaches are applied to the same full-scale turbine blade, and the resulting blade designs are compared.

2. Approach

In this section, the two scaled blade design approaches are discussed in detail.

2.1. Circulation-based Design

The circulation approach assumes that the spatial distribution of circulation and tip-speed-ratio are most important to creating a scaled wake. The dimensionless circulation $\Gamma'$ is a function of blade span

$$\Gamma' = \frac{C_l}{2} \frac{W}{R U_\infty}.$$  

The full scale wind turbine’s performance was found using blade element momentum theory. The circulation distribution became the objective function for spatial loading. The other objective function is the spatial distribution of lift coefficient. A value of 0.6 was chosen for these DU airfoils because it allowed for a safe stall margin, was close the maximum lift-to-drag ratio of the tip airfoil, and lead to a reasonably large chord. A large chord means thicker absolute airfoil sections that are easier to manufacture with accuracy at small scales. The inverse design code was then run, which solved for the necessary chord and twist to match the prescribed circulation and lift coefficient distributions. Further details of the inverse design algorithm are discussed in Kelley et al [10].

2.2. Normalized forces design

An inverse design code was developed to design a blade that matches the normalized normal and tangential force distributions. Once the user specifies the target normal and tangential force distribution, tip-speed ratio, and airfoil shape, the inverse design code uses a blade element
momentum (BEM) theory inverse design approach to determine the blade chord and twist angle distributions. BEM is a theory that combines both blade element theory and momentum theory. It is commonly used to design and analyze propellers and wind turbine blades.

To start the process, the large wind turbine’s normal and tangential forces under specific inflow conditions were prescribed, and the normal and tangential forces for sub-scale blade were computed by setting the normalized normal and tangential forces for full-scale and sub-scale wind turbines equal. Using these target forces, the flow parameters (induction factor, tangential induction factor, and inflow angle) were determined from momentum theory using an iterative process. Due to the high number of unknown variables against available equations, initial chord values were assumed to compute the Reynolds number and to determine airfoil lift and drag. The tool Xfoil [12], an open source code, was employed to compute aerodynamic coefficients over a range of angle of attack. The main reason for using the Xfoil program was to reduce the computation time during the design process. Using these aerodynamic coefficients, the target $C_l/C_D$ determined from full-scale was used to determine the angle of attack. This process was repeated until reaching the appropriate chord length. Using the determined angle of attack and inflow angle, the twist angle was obtained. Repeating this process along the span of the blade yielded the overall blade design. The Prandtl tip loss function was utilized in the design process. A detailed flowchart of normalized force distributions design approach can be found in Fig. 1, which provides the steps used to determine the sub-scale wind turbine blade shape.

Figure 1. Flowchart of the code for designing a blade using the normalized forces approach
3. Results

3.1. Case study

In this study, the NREL WindPACT 1.5 MW turbine was considered as the reference full-scale wind turbine. The NREL design code FAST [13] was used to calculate the force distributions of full-scale turbine. FAST is commonly used to perform aero-elastic simulations of wind turbines. To determine the aerodynamics forces, FAST employs AeroDyn, which uses both BEM theory and a generalized dynamic wake model, and applies several other corrections to account for tip and hub losses, dynamic stall, and skewed wake effects.

The airfoil geometry along the sub-scale blade was chosen to be similar to that of a commercial wind turbine starting with thick airfoils near the blade root and transitioning to thin airfoils near the blade tip. Five high Reynolds number DU airfoils ranging in maximum relative thickness from 18% to 35% chord were chosen for these designs, and both pressure and suction sides were tripped to induce a turbulent boundary layer. There are many articles in which the capability of Xfoil is tested and verified, (eg. references 14, 15). Xfoil output results for the aerodynamic characteristics of DU-series airfoils were compared with experimental data reported in Ref. [16], as shown in Fig. 2. The validation Re numbers for different airfoils can be found in Table 1. The results demonstrate the capability of Xfoil for predicting the lift coefficient for the DU airfoils at moderate Re, particularly in the linear region, which is the primary region of interest in this work.

| Airfoil   | t/c (%) | Re     |
|-----------|---------|--------|
| DU-95-W-180 | 18      | 340,000 |
| DU-91-W2-250 | 25      | 280,000 |
| DU-97-W-300 | 30      | 220,000 |

Figure 2. Comparison of Xfoil data with experimental data [16] for DU airfoils
3.2. Circulation-based Design

Fig. 3 shows the circulation distribution for full-scale and sub-scale wind turbines. As intended, the circulation matches the full-scale blade design. The only difference is found in the root region. The full-scale blade design uses a lift interpolation routine for predicting lift of a thickened airfoil, whereas Sandia’s code interpolates from the lift-to-drag ratio. In addition, the aerodynamic performance is relatively unknown since the shape is a blended airfoil and circle hybrid and rotational augmentation may further affect the actual performance.

![Figure 3. Circulation distribution for the target blade and the sub-scale blade designed using the circulation-based approach](image)

3.3. Normalized forces design

Using the forces obtained from FAST for the target wind turbine, the normalized force distribution design approach was applied as discussed above. The normal and tangential force distributions of the sub-scale blade are shown with the target force distributions in Fig. 4. These results demonstrate that the normal and tangential forces matching requirements have been met. Due to the constraints applied to the sub-scale turbine blade design, there are small gaps between the force distributions of sub-scale turbine and target values. Differences observed in the tip region generally arise from the difference between the target L/D ratio and the L/D from the airfoil data. As shown in Fig. 5, the target L/D ratios and sub-scale L/D ratios match well in the root region, but are different in the tip region. This occurs because the maximum L/D ratios determined for the airfoils used in these locations are smaller than the target L/D ratios, which is caused by Re effects. As a result, the maximum L/D ratio for the airfoils are used in the tip region.

3.4. Comparison of the two approaches

Blades have been designed using the two approaches as discussed above, but the question remains as to how different the designs are. The chord and twist angles of the blades that produce the target circulation for first approach and normal and tangential forces for second approach can be found in Fig. 6. Due to the abrupt changes in target circulation and target normalized force distributions, both designs lead to small step in chord distributions at $r/R = 0.55$. Using a
Figure 4. Normal and tangential force distribution for target blade and sub-scale blade designed using the normalized forces approach.

Figure 5. Lift-to-drag ratio along the blade for the normalized forces approach

more realistic target blade geometry would likely result in a much smoother result. As can be observed from both designs, the chord and twist angle start at their maximum values at the root and decrease moving towards the blade tip, which is consistent with commercial small wind turbine blade geometries. It is also observed that the normalized forces approach leads to higher chord and twist angle in the root region, but the circulation approach results in higher values for the blade chord and twist angle for $r/R > 0.35$. The airfoil distributions along the blades are also compared for the two approaches. There is a relatively large difference in the root region, but then the two approaches use almost the same airfoils along the remainder of the blade.

Another important comparison is the circulation and force distributions that results from the two designs. Fig. 7 shows the target circulation and circulation obtained from two blades. As expected, the circulation approach leads to a better match for circulation distribution in
comparison with the force approach. However, for the normal and tangential force distributions, the force approach leads to better results. The results show that, even though the magnitudes are different for some of the comparisons, the trend is similar for all cases.

**Figure 6.** Comparison of the geometry produced by the two design approaches.

**Figure 7.** Comparison of the forces and circulation predicted for the two designs.

Table 2 shows the chord-based Re number range for full-scale and sub-scale blades. As expected, the Re range for the full-scale blade is millions, but for sub-scale blades it ranges from 100,000 to 350,000 for the circulation method and from 180,000 to 240,000 for the forces method.

The integrated normal and tangential forces across the blade may be used to determine the power and thrust coefficients. These values are tabulated in Table 3. Both designs predict the same efficiency, but the thrust coefficient is lower for the normalized forces design approach. This implies that the wake strength will be slightly lower for the matched force design approach relative to the matched circulation approach.
Table 2. Re range along the blade span for full-scale and sub-scale blades.

| Wind Turbine blade                     | Radius (m) | Re range   |
|----------------------------------------|------------|------------|
| Full scale (NREL 1.5 MW)               | 35         | 3-6 million|
| Sub-scale (Circulation approach)       | 1          | 100,000-350,000|
| Sub-scale (Forces approach)            | 1          | 180,000-240,000|

Table 3. Comparison of thrust and power coefficients for the two design approaches

| Approach   | $U_\infty$ (m/s) | $\lambda$ | $C_P$  | $C_T$  |
|------------|------------------|-----------|--------|--------|
| Circulation| 15               | 7         | 0.347  | 0.589  |
| Forces     | 15               | 7         | 0.342  | 0.535  |

Although the geometry, forces, and circulation for the two blade designs are relatively close, it is useful to compare the resulting blade appearance. Figs. 8 and 9 show solid models of the resulting blade designs for the two design approaches. It can be seen that the blade shapes are similar and appear very much like the modern wind turbines blades.

![Figure 8. Solid model of the blade shape for circulation approach](image8)

![Figure 9. Solid model of the blade shape for forces approach](image9)

In Fig. 10, the induction factor from the target wind turbine is compared with the induction factors for the designed blades. The induction factor is an important parameter in blade design and wake studies as it is representative of the near wake axial velocity deficit. It is observed that both approaches produce different values than the target axial induction factor in some locations, and the circulation approach is higher than both the target value and that from the normalized force design approach over most of the blade.

4. Conclusion

Two approaches have been developed to design sub-scale blades that are expected to produce a wake with characteristics similar to that of an industrial scale turbine. This is accomplished by enforcing either similar circulation distributions or similar normalized force distributions.
The circulation design methodology does not consider drag to be an important force to scale the blade since only lift per unit span is maintained. This leads to a difference in the normal force per unit span. The circulation designed blade also has higher solidity because the design lift coefficient is smaller than that of the force distribution method. In the force distributions matching approach, the load distributions for full-scale and sub-scale turbines are closely matched. The results indicate that the designs from the two approaches result in slightly different blade shapes.

The circulation approach has been used to design a sub-scale blade (13 m length) for the SWiFT facility that will be tested as part of the DOE’s National Rotor Testbed project. The goal is to use these blades to study wind turbine interactions, and to take high fidelity measurements of wind turbine wakes. The normalized forces approach will be employed to design a smaller blade (1 m length) that will be manufactured and instrumented for testing in a controlled inflow environment (e.g. in a large wind tunnel).

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