Aerodynamic Design of Megawatt Wind Turbine Blades with NPU-WA Airfoils

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Abstract. The NPU-WA airfoils were designed at high design lift coefficient and high Reynolds number, with small sensitivity of the maximum lift coefficient to leading edge roughness and excellent geometric compatibility. Compared to the widely used airfoils, the NPU-WA airfoils have higher lift-to-drag ratio and higher maximum lift coefficient. This paper aims to design a megawatt wind turbine blade in order to demonstrate the advantage of the NPU-WA airfoils. The distributions of chord length and twist angle for a 2 MW wind turbine blade are optimized by a kriging surrogate model-based optimizer, with aerodynamic performance being evaluated by blade element-momentum theory. Results show that compared with the baseline blade, the maximum power coefficient of the optimized NPU blade is larger, and the chord lengths at all span-wise sections are smaller, which is benefit to structural weight reduction. It is shown that the NPU-WA airfoils feature excellent aerodynamic for the design of megawatt wind turbine blades.

1. Introduction
As a renewable and clean energy, wind energy is favoured by people from all over the world. According to the statistics from Global Wind Energy Council (GWEC)[1], the installed capacity will reach 840 GW in the year of 2022.

The aerodynamic performance of airfoils has a significant influence on the aerodynamic characteristics of a wind turbine blade. Before 1990s, wind turbine blades were designed by using the conventional aeronautic airfoils, such as the NACA (National Advisory Committee for Aeronautics) 6-series (NACA63, NACA64, etc.) and four-digit airfoils (NACA 44-series). Since the late 1980s, research on advanced airfoils for wind turbines has been carried out in the United States of America and Europe, such as the S-series airfoils designed by National Renewable Energy Laboratory (NREL) of the United States[2][3], the DU-series airfoils designed by TU Delft of the Netherlands[4], the RISØ-series airfoils designed by RISØ Laboratory of Denmark[5][6], and the FFA-series airfoils designed by National Aeronautical Research Institute of Sweden[7]. In 2011, the Northwestern Polytechnical University (NPU) of China developed a new family of airfoils for megawatt wind turbines, named NPU-WA[8]-[11], and a family of airfoils for multi-megawatt wind turbines, named NPU-WA[12]. The airfoils feature a high lift-to-drag ratio at a high Reynolds number and a high lift coefficient. The Chinese Academy of Sciences (CAS) designed a family of airfoils for medium Reynolds numbers, named CAS[13]. The Chongqing University of China and Technical University of
Denmark developed the CQU-DTU-series airfoils, taking into account of the aerodynamic performance and low noise requirements[14].

Supported by the National High Technology Research and Development Program ("863" Program) of China, a new airfoil family, named NPU-WA, for megawatt wind turbine blades was designed by Qiao et al.[8], and improved by Han et al.[9]-[11]. The main improvements are reducing the sensitivity of the maximum lift coefficient to leading edge roughness and improving geometric compatibility. The airfoils have applied for invention patents of China[15]-[18], and have been authorized.

The objective of this paper is to demonstrate the advantage of the newly developed NPU-WA airfoils in improving wind energy capturing, by carrying out an aerodynamic optimization design of 2 MW wind turbine blades. The remainder of this paper is organized as follows. In Section 2, the developed NPU-WA airfoils are introduced, including geometric shapes and the aerodynamic performance test in the NF-3 wind tunnel. Section 3 describes the design optimization method of megawatt wind turbine blades, including the aerodynamic analysis models and validation, mathematical model of optimization. Section 4 presents the results and discussion, including the design optimization of megawatt wind turbine blades with NPU-WA airfoils, and a comparison of aerodynamic performance between the baseline blade and the optimized blade. The last section is for the conclusions.

2. Review of NPU-WA airfoils
The geometric shapes of the NPU-WA airfoils are shown in Figure 1. These airfoils are designed for achieving a high lift-to-drag ratio at high design lift coefficients (>1.2). A high lift-to-drag ratio helps to improve the aerodynamic performance and wind energy capturing of a wind turbine. A high design lift coefficient is beneficial for reducing the chord length of a blade, resulting in a structural weight reduction. The design Reynolds numbers for airfoils at outboard of the blade are 5 million to 6 million, corresponding to NPU-WA-210, NPU-WA-250, NPU-WA-300, respectively.

![Figure 1. Geometric shape of the NPU-WA wind turbine airfoils.](image)

The NF-3 low-speed wind tunnel of Northwestern Polytechnical University is used to validate the aerodynamic performance of the NPU-WA wind turbine airfoils. Compared to DU airfoils, the NPU-WA airfoils have a higher maximum lift coefficient, higher lift-to-drag ratio, and higher design lift coefficients (corresponding to the maximum lift-to-drag ratio), shown in Figure 2. It is noted that the design lift coefficient of NPU-WA airfoils is higher than 1.2.

3. Design Optimization of a Wind Turbine Blade
Computational fluid dynamic (CFD) methods, such as the Reynolds-averaged Navier–Stokes (RANS) simulation[19], delayed detached eddy simulation (DDES)[20], and large eddy simulation (LES) are high fidelity tools for wind turbine blade design. However, they are too consuming for an optimization design. Instead, the blade element-momentum (BEM) theory[21] is widely used in engineering applications[22][23], for its reasonable results and much lower cost. In this paper, the BEM theory is used to evaluate the aerodynamic performance for the optimization design of a wind turbine blade.

The Phase VI wind turbine blade[19][24] (Figure 3) designed by NREL is used to validate the
BEM method used in this study. The wind turbine consisted of two blades with a radius of 5.03 m. Figure 4 shows that the results of BEM method agree well with the experimental data.

Figure 2. Comparison of experimental data for the NPU-WA-210 airfoil and DU93-W-210 airfoil.

Figure 3. NREL Phase VI wind turbine blade.

Figure 4. Comparison of experimental data, reference results, and present results of shaft torque.

The design goal is to maximize the maximum power coefficient ($CP_{\text{max}}$), the design variables were chord lengths and twist angles at 13 control sections, and the constraints included the optimal tip-speed ratio, power coefficients at a high tip-speed ratio, chord, and twist of control sections. The mathematical model of optimization can be expressed as follows:

$$\begin{align*}
\text{max} & \quad f(x) = CP_{\text{max}} \left[ x = \left( \text{chord}(i), \text{twist}(i), i = 1, 17 \right) \right]; \\
\text{s.t.} & \quad g_1(x) = 11 - \lambda_{\text{opt}} > 0; \\
& \quad g_2(x) = CP_{x=12} - CP_{0, x=12} > 0; \\
& \quad g_3(x) = CP_{x=14} - CP_{0, x=14} > 0; \\
& \quad g_4(x) = \text{chord}(j - 3) - \text{chord}(j - 2) > 0 (j = 4, 15); \\
& \quad g_5(x) = \text{twist}(j - 15) - \text{twist}(j - 14) > 0 (j = 16, 25); \\
& \quad g_6(x) = \text{twist}(j - 14) - \text{twist}(j - 15) > 0 (j = 26, 27)
\end{align*}$$

(1)

where, $\lambda$ is tip-speed ratio, $CP$ represents the power coefficient, $CP_{\text{max}}$ represents the maximum power
coefficient, $\lambda_{opt}$ represents the optimal tip-speed ratio corresponding to the maximum $CP$, the subscript “0” represents the performance parameters of the baseline blade. Chord and twist represent the chord length and twist angle of each control section of the blade, respectively. The numbers in brackets represent the serial number of the control section from root to tip, where “1” denotes the blade root, and “13” denotes the blade tip.

An in-house surrogate-based optimizer, “SurroOpt”, was used for the optimization design of the wind turbine blade. This optimizer is proven to be efficient and robust, and more details about this method are presented in References [25]-[29].

4. Results and Discussion
With the overall technical parameters shown in Table 1, a 2 MW wind turbine blade was optimized. The span-wise airfoil arrangement is shown in Figure 5. Figure 6 shows the convergence history of the optimization design. Figure 7 shows the optimized shape, named NPU blade.

Table 1. Overall technical parameters of the 2 MW wind turbine.

| Parameter                              | Value                        |
|----------------------------------------|------------------------------|
| Rated power                            | 2 MW                         |
| Blade length                           | 51.5 m                       |
| Diameter of Wind mill                  | 105.4 m                      |
| Number of blades                       | three                        |
| Power adjustment mode                  | Variable-pitch and variable-speed |
| Cut-in wind speed                      | 3 m/s                        |
| Cut-out wind speed                     | 25 m/s                       |
| The minimum rotational speed of motor  | 10 rpm                       |
| The rated speed of motor               | 16 rpm                       |
| Height of Hub                          | 82 m                         |
| Driving mode                           | Direct drive                  |

Figure 5. Span-wise airfoil arrangement of the designed 2 MW wind turbine blade.

Figure 6. Convergence history of optimization.

Figure 7. 3D model of the designed blade.
A baseline blade is used to demonstrate the advantage of the NPU-WA airfoils. Figure 8 and Figure 9 show that the aerodynamic performance of the optimized blade is slightly improved. Figure 10 demonstrates the comparisons of geometric parameters between the baseline blade and optimized blade. It is noted that both the chord length and absolute thickness were reduced, which contributed to the structural weight reduction of the blade. This improvement is mainly due to the high design lift coefficient of NPU-WA airfoils.

Figure 8. Comparison of power coefficient.

Figure 9. Comparison of power.

(a) chord length distribution

(b) twist angle distribution

(c) relative thickness distribution

(d) absolute thickness distribution

Figure 10. Comparison of geometric parameters between the baseline blade and the optimized blade.

5. Conclusions
A 2 MW wind turbine blade is optimized by using the newly developed NPU-WA airfoils. Due to the higher lift-to-drag ratio of NPU-WA airfoils, the maximum power coefficient is increased. Due to the
high design lift coefficient of NPU-WA airfoils, both the chord length and absolute thickness are reduced, which contributed to reducing the structural weight of the blade.

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References
[1] GWECS 2018 Global Wind Report 2017—Annual Market Update
[2] Tangler J L, Somers D M 1995 NREL/TP-442-7109
[3] Somers D M 2005 NREL/ER-500-36339
[4] Timmer W A, Van Rooij R P J O M 2003 J. Sol. Energ.-T ASME 125 11
[5] Fuglsang P, Bak C 2001 AIAA-2001-0028
[6] Fuglsang P, Bak C, Gauana M, Antoniou I 2004 AIAA-2004-0668
[7] Björck A 1990 FFA/TN-1990-15
[8] Qiao Z D, Song W P, Gao Y W 2012 Acta Aerodyn. 30 260 (In Chinese)
[9] Han Z H, Song W P, Gao Y W 2013 Appl. Math. Mech. 34, 1012 (In Chinese)
[10] Han Z H, Zhang K S, Liu J, Song W P 2013 AIAA-2013-1108
[11] Han Z H, Song WP, Gao Y W, Chen J 2016 Appl. Math. Mech. (Engl. Ed.) 37 S67.
[12] Xu J, Han Z, Yan X, Song W 2019 Energies 12 3330
[13] Bai J Y, Yang K, Li H L 2010 J. Eng. Thermophys. 31 589. (In Chinese)
[14] Cheng J T, Zhu WJ, Fischer A, et al 2014 Wind Energy 17 1817.
[15] Qiao Z D, Song W P, Gao Y W, et al 2012 Patent Number: ZL 201110023215.1
[16] Han Z H, Xu J H, Yu L, et al 2016 Patent Number: ZL 201410270941.7
[17] Han Z H, Song W P, Xu J H, et al 2017 Patent Number: ZL 201610164780.2
[18] Han Z H, Xu J H, Yu L, et al 2017 Patent Number: ZL 201410269752.8
[19] Sørensen N N, Michelsen J A, Schreck S 2002 Wind Energy 5 151
[20] Qian G W, Ishihara T 2019 J. Wind Eng. Ind. Aerodyn. 191 41
[21] Hansen M O L 2008 Aerodynamics of Wind Turbines 2nd ed. (London: Earthscan) p 16
[22] Ge M, Wu Y, Liu Y, et al 2019 Appl. Energy 233 975
[23] Ge M, Wu Y, Liu Y Q, et al 2019 Energy 141 46.
[24] Giguére P, Selig M S 1999 NREL/ER-500-26173
[25] Liu J, Song W P, Han Z H, et al 2017 Struct. Multidiscip. Optim. 55 925
[26] Zhang K S, Han Z H, Gao Z J, et al 2019 Struct. Multidiscip. Optim. 59 421.
[27] Han Z H, Xu C Z, Zhang L, et al 2019 Chin. J. Aeronaut. doi:10.1016/j.cja.2019.05.001
[28] Zhang Y, Han Z H, Zhang K S 2018 Struct. Multidiscip. Optim. 58 1431
[29] Liu F, Han Z H, Zhang Y, et al 2019 Aerosp. Sci. Technol. doi:10.1016/j.ast.2019.105345