Blunt-Wavy Combined Trailing Edge for Wind Turbine Blade Inboard Performance Improvement

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Abstract. Aerodynamic performance of wind turbine blade inboard is improved by modifying its trailing edge shape. A combined trailing edge modification design with blunt trailing edge and a span-wise wavy trailing edge is used. Designing blunt trailing edge at the blade inboard makes the flow become more attached than the conventional sharp trailing edge. The span-wise wavy trailing edge breaks up the Karman vortex shedding generated by the blunt trailing edge. The Sandia National Laboratory 100 meter blade, SNL100-03 was used as a baseline model. Rotating blade simulations are performed with the full-scale isolated rotor condition. Aerodynamic performance analysis and aeroacoustic performance analysis of the modified turbine blades are performed. By using the blunt-wavy combined trailing edge modification, the massive flow separation at the inboard of the baseline blade is prevented successfully. Delayed Detached Eddy Simulation (DDES) with a modified laminar-turbulent transition model (Medida - Baeder model) is used for better prediction of flow separation.

1. Introduction
Blade root power loss is one of the major power losses along with the tip loss in the wind turbines. A main source of the blade root power loss is massive flow separation due to the thick airfoil or even oval shape of the blade root. Although power generation at the blade inboard is not as large amount as of the mid or outboard power generations (because of lower local flow velocities), it is definitely massive loss in the calculations of the Annual Energy Production (AEP). The idea of the blunt trailing edge design has been proposed to delay the onset of the flow separation for the thick airfoils by previous studies [1,2]. In the previous studies, the blunt trailing edge prevented the flow separation onset. However, in some cases, the blunt trailing edge emanated Karman-like trailing edge vortex structure in the wake. This vortex structure in the wake is a severe source of acoustic noise emission, which detracts from the “clean energy source” image of a wind farm. This strong and periodical trailing edge vortex structure can be eliminated by another trailing edge modification. As a noise reduced trailing edge design of the blunt trailing edge airfoils, we have proposed the so called, ‘the span-wise wavy trailing edge modification’. In the previous studies, it has been verified that the span-wise wavy trailing edge breaks up the Karman-like trailing edge vortex structure of the blunt trailing edge airfoils [3,4]. Regarding the previous researches, it will be promising that the use of the Blunt-Wavy combined trailing edge modification helps to improve the aerodynamic and aero-acoustic performance at the blade inboard.
In the current study, the Blunt-Wavy combined trailing edge modification for the inboard flow improvement is proposed and effects of the Blunt-Wavy combined trailing edge are investigated using CFD. The SNL 100 meter blade (SNL100-03FB) [5] has been used as a baseline. The aerodynamic and aero-acoustic behaviors of the baseline and modified blade are presented and discussed.

2. Blunt-Wavy Combined Trailing Edge Design

The principal design idea of the blunt-wavy trailing edge is to increase the trailing edge thickness from the sharp trailing edge and then to alter the local trailing edge thicknesses of the blade in the span-wise direction, as shown in Figure 1. The blunt trailing edge will prevent the onset of the separation flow, and the span-wise wavy patterns on the trailing edge will prevent the onset of the Karman-like vortex shedding. As a result, the power loss at the inboard due to the massive separation will be recovered and the inboard wake will be more tranquil than both the baseline blade and the blunt only modified blade. In the current study, the SNL100-03FB blade is modified using the Blunt-Wavy combined trailing edge modification. From the previous test [6], we found the flatback trailing edge of the SNL100-03FB prevents flow separation onset near the mid-span region, but not very effective at the closest to the root region. Thus, for the first process of the Blunt-Wavy modification, trailing edge thickness is increased by 50% of the original blade at the blade inboard region, from r/R ~ 0.1 to 0.3, where the span-wise location of root is r/R = 0 and the tip is 1. Proper wave size has been studied in the previous work [6], and the less portion wavy trailing edge, ‘4W-75%t-10%c’ is selected in the current study. The term, ‘4W’, means the pattern has four waves per every 1 chord length in the span-wise, and the term, ‘75%t’ means the trailing edge thickness of the wave trough is 75% of the trailing edge thickness of the blunt trailing edge. The last term, ‘10%c’ means the chord-wise portion of airfoil where the wavy modification is applied.

Figure 1 Example of the 4W-75%t-10%c wavy trailing modification (left), and modification process of the Blunt-Wavy combined trailing edge (right)

Figure 2 Aerodynamic and aero-acoustic performance of the flatback and the span-wise wavy trailing edge ‘4W-75%t-10%c’
The drag and noise reduction effect of the ‘4W-75%-t-10%\textit{c}’ wavy trailing edge for the flatback airfoil has been verified in the previous study [6]. DDES has been performed for the wavy trailing edge airfoil and the ‘FB series’ airfoils (FB3500-1750, 0462, 0050). In Figure 2, a drag polar, a noise spectrum, and trailing edge vortex structure of the wavy trailing edge airfoil is presented. Briefly, the wavy trailing edge decreases the drag down to the values of the sharp trailing edge airfoil in the range of the angle of attack, 0 to 12°, and mitigates the tonal noise of the flatback trailing edge by more than 30dB, due to the break up of the strong span-wise coherent trailing edge vortex structure. Details of the results and validations are presented in the previous publication [6].

3. Numerical Methods
Because of the complex trailing edge geometries, which create highly unsteady vortical flow, a full three-dimensional Navier–Stokes solver is utilized in a rotating overset grid system. A lower-fidelity model such as Blade Element Momentum (BEM) methods or vortex trace methods may not be able to accurately represent the physical phenomena. Furthermore, to resolve the aperiodic turbulent flow near the trailing edge, a Delayed Detached Eddy Simulation (DDES) is also included in conjunction with a \( \gamma - Re_{\theta} - \text{SA laminar-turbulent transition model} \) (Medida and Baeder) [7]. In the current study, in-house developed CPU-based parallel Navier-Stokes solver, the OVERTURNS is used. The OVERTURNS (Overset Transonic Unsteady Rotor Navier-Stokes) is structured, finite-volume, compressible solver. The 3rd order accurate MUSCL (Monotonic Upwind Scheme for Conservation Laws) scheme [8] with Koren’s limiter [9] is used for spatial reconstruction of the primitive variables and 2nd order accurate implicit BDF (Backward Differential Formula) is used for time integration. The governing equations are linearized and solved using the LUSGS (Lower-Upper Symmetric-Gauss-Seidel) approximate factorization method [10]. Dual time stepping is employed to minimize factorization errors. Roe’s approximate Riemann solver [11] is used to evaluate inviscid flux term and 2nd order accurate central difference scheme is used to evaluate viscous flux terms. The one equation Spalart-Allmaras turbulent model [12] combined with the \( \gamma - Re_{\theta} - \text{SA transition model} \) is used for computing the eddy viscosity field. Turkel’s low-Mach pre-conditioner [13] is used to improve convergence and accuracy in the low-speed flow regime. The solver has been validated for the SNL 100 meter blade problem in the previous study [6].

4. Computational Meshes
A set of overset meshes is used for the current study. The mesh system consists of a single blade mesh overset to a cylindrical background mesh as presented in Figure 3 and 4. The blade mesh is constructed with a structured O-O topology, which dimensions of 269 x 380 x 85 in the wrap-around, span-wise, and wall-normal directions. The cylindrical background mesh is also structured mesh, which dimensions of 184 x 388 x 320 in the azimuthal, radial, and axial direction, and 120° of extent in the azimuthal direction. The mesh also has an extent of 4 times of rotor blade radius in the radial direction, and 11 times of rotor blade radius in the axial direction. For an isolated rotor simulation, these mesh extensions are good enough to meet a far field boundary condition. The finest grid spacing in the blade inboard regions of the background mesh is 0.01 of chord length, and 0.05 of chord length near the blade tip. The size and resolution of the current mesh system has been validated in the previous work [6].
5. Results and Discussions

5.1 Aerodynamic Analysis

The test conditions are presented in Table 1. The original version of the SNL100-03FB, the blunt trailing edge modified SNL100-03FB, and the Blunt-Wavy combined trailing edge modified SNL100-03FB are tested at the same flow conditions and compared each other. Results of the turbine power prediction are presented in Table 2. By the only blunt trailing edge modification, the turbine thrust and power are increased by 1.23% and 1.45% respectively. The Blunt-Wavy trailing edge modification slightly increases the thrust and power of the blunt trailing edge modified blade, thus it improves the turbine thrust and power by 1.56% and 2.62% respectively.

| Wind speed (m/s) | Rotor speed (rpm) | Max.Re#     | Blade pitch angle (°) |
|------------------|-------------------|-------------|-----------------------|
| 11.3 m/s         | 7.401             | 5.273 x 10⁶| 0.0                   |

Table 2 Turbine power prediction

| Blade type                  | Thrust (kN) | ΔT (%)   | Power (MW) | ΔP (%) |
|-----------------------------|-------------|----------|------------|--------|
| SNL100-03FB                 | 1858.4      | -        | 14.52      | -      |
| Blunt TE modified           | 1881.2      | +1.23%   | 14.73      | +1.45% |
| Blunt-Wavy TE modified      | 1887.3      | +1.56%   | 14.90      | +2.62% |

Time-averaged span-wise air-load distributions are presented in Figure 5. Aerodynamic loss, due to the massive flow separation, is observed at the inboard region of the original version of the SNL100-03FB blade, from the root to 0.25 r/R. The massive flow separation at the inboard is clearly observed in the vorticity contours presented in Figure 6 and 7. In the SNL100-03FB blade design, the span-wise location between 0.1 – 0.3 r/R is a transition region between the cylindrical root section and the airfoil section. In this location, the airfoils are relatively thick therefore it causes the separation onsets. This massive inboard separation is prevented by the blunt trailing edge modification.

The 50% increased trailing edge thickness (blunt trailing edge modification) at the region lowers the steep airfoil slopes, and it delays the growth of the adverse pressure gradient. By the blunt trailing edge modification, both the out of plane and the in plane air-loads at the inboard are recovered, and the inboard aerodynamic performance is much improved. In the figure 6 and 7, the trailing edge vortex strength at the location between the root and the 0.2 r/R is weaker than the original SNL blade. However, now there is a strong vortex shedding at the blade span between 0.2 – 0.3 r/R. The trailing edge vortex shedding is now more span-wise coherent comparing to the baseline blade.

Adding the span-wise wavy modification on the blunt trailing edge modified blade doesn’t change the rotor thrust in the current case, and the power generation is actually increased by reducing the pressure drag of the blunt trailing edge. The wavy trailing edge disturbs the flow near the trailing edge and generates small local flow separations at the each wave paves, and it slightly decreases the thrust recovery achieved by the blunt trailing edge.
edge modification. However, in the current tests, the design of very small portion of wavy modification minimizes the lift loss and maximizes the drag reduction, and it still provides the power and thrust improvement at the blade inboard. The trailing edge vortex shedding still exists at the 0.2 – 0.3 r/R, but now the vortex strength is much weaken. In the figure 7, the difference of the trailing edge vortex shedding depending on the trailing edge modifications is clearly verified. The vortex from the blunt trailing edge modified blade and the Blunt-Wavy trailing edge modified blade sheds periodically. It notes that the periodic vortex shedding may cause the tonal noise emission, depending on the vortex strength and shedding frequencies.

Figure 5 In/out of plane sectional load distribution in the blade span

Figure 6 Inboard trailing edge vortex shedding in the iso-vorticity contours

Figure 7 Comparison of the trailing edge vortex shedding at the blade inboard 0 to 0.3 r/R
5.2 Aero-acoustic analysis

The acoustic pressure history is measured around the blade inboard region. The measurement locations are described in Figure 8. Total eight measurement points locate around the blade at 3 times of chord length away from the blade, and at 0.165 r/R of the blade span. With the measurement setups, since the measurement locations are following the blade motion, there is limitation to measure the sound propagation to the surrounding ground from the turbine. In the current study, since acoustic analysis focuses on verifying a source of tonal noise, the isolated rotor assumption and the acoustic measurement setup is selected despite of the limitation. The sampling rate is 0.001s\(^{-1}\), and the data measured for 2.5revs. The blade rotation frequency is about 0.123Hz. The 1/3 octave band filtered FFT (Fast Fourier Transform) results are presented in Figure 8. In the figure, a wind blows from the top to the bottom, and the blade rotates from the right to the left. Thus the turbine inboard wake affects to the pressure field at the measurement locations 3, 4, 5, and 6, and rarely affects to the locations 1, 2, 8, and 7.

At the most of measurement locations, the blunt trailing edge generates higher magnitude and tonal noise around a 5Hz frequency range. With an exception, at the measurement location 4, higher magnitude noise is measured in the original blade. This is rarely tonal, but linearly decays at the higher frequency ranges, and it must be caused by the massive separation of the original blade inboard. In the results of the blunt trailing edge modification, the tonal noise signals are observed at the most of the measurement locations with frequencies of 2.5Hz through 5Hz. The noise measured at the wake region has much higher magnitude than it measured at the rotor upstream region. However, also at the rotor upstream region, still the tonal signals are observed even though the magnitude of the signal is much smaller. It verifies the propagation of the tonal noise from the trailing edge to the blade surround.

![Figure 8 1/3 octave band filtered acoustic noise at blade inboard](image-url)
Figure 9 Comparison of instantaneous inboard wake structures between the SNL100-03FB blade and the trailing edge modified blades

By the Blunt-Wavy trailing edge modification, the strong tonal noise of the blunt trailing edge is mitigated. At the measurement location 3, the tonal noise magnitude is decreased by 15dB, and the frequency is shifted slightly higher band. Similarly, the noise magnitude of the Blunt-Wavy trailing edge is less than the blunt trailing edge at the other measurement locations. It is obvious that there is a strong relation between the tonal noise and the periodic Karman-like trailing edge vortex shedding of the blunt trailing edge. In Figure 9, the vortex shedding patterns in the turbine inboard wake are compared. In the figure, it is found that the wake of the Blunt-Wavy modified blade is much tranquil compared with other two blades.

6. Conclusion

Current study proposed and verified the new design for a wind turbine blade inboard performance improvement. Modern large turbine blades tend to be designed with relatively thick airfoils at the blade inboard region. It improves the structural performance, but the thick airfoils are easy to get separation. In the current study, the Blunt-Wavy trailing edge modification delays the onset of the separation, recovers aerodynamic performance at the blade inboard. By the aerodynamic performance recovery, the thrust and power of the rotor increase by around 1.56% and 2.62%. It could be notable improvement as it counts in AEP.

The tonal noise emission of the blunt trailing edge is not desirable for the wind turbine design. Even though the low frequency band noise may not audible for human beings, it may affect badly to the human body when it’s exposed for a long periods. For the issue of the noise, the Blunt-Wavy combined trailing edge modification reduces the noise by more than 15dB, and it mitigates propagating the high magnitude pressure fluctuation. It is similar to the results of the previous airfoil tests [3], [4], and [6]. Many other different sizes of the wavy trailing edge have been developed in the previous studies during the past few years. Among them, the ‘4W-75%-t-10%%c’ was selected for the current study. The wavy trailing edge design changes very small portion of the original blade design, but works well as a drag and noise reducer. This is encouraging because one can minimize the concerns of the structural characteristic changes as improves the aerodynamic and aero-acoustic performance of the turbine blade.

However, yet it is not very clear the effect of the Blunt-Wavy trailing edge modification for the field test, because the current study was performed under the isolated blade conditions. There might be slight difference when it includes other turbine configurations, such as a tower and nacelle. In addition, comprehensive acoustic
measurements with an extended background mesh might provide more comprehensive understanding of the proposed modification design.

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